High Performance Concrete with High Volume Ultra Fine Fly Ash Reinforced with Basalt Fibre

A thesis submitted in fulfillment of the requirements for
the degree of Doctor of Philosophy

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2012

DECLARATION

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Mochamad Solikin

25 June 2012

Acknowledgment

I would like to express my sincerest gratitude to my supervisors, Dr Indubhusan Patnaikuni and A./Prof. Sujeeva Setunge, who have supported me throughout my thesis with their patience and knowledge whilst allowing me the room to work in my own way. I will always be grateful to them for their encouragement not only in finishing this project but also in helping me disseminate my research result that would be valuable for my research career in the future.

DIKTI scholarship from The Ministry of National Education Indonesia and the support from my home institution, Muhammadiyah University of Surakarta Indonesia gave me the opportunity to come to Australia to study as a full-time postgraduate research student. I am very grateful for all the support that I received throughout my candidature.

In various laboratories work I really appreciate the support from Pavel Ryjkov as Civil Engineering laboratory coordinator for giving me access to all facilities in civil engineering laboratory of RMIT University. In addition, I would like to thank the support from Civil Engineering laboratory staffs (i.e. Bao Thach Nguyen, Saravanan Mani, Ramesh Dilipsingh, Kevin Le, and Mathew Leung) in preparing equipment and facilities to conduct my laboratory experiments. In addition, I appreciate Philip Francis and Peter Rummel who trained me very well, helped and gave me access to conduct micro structure analysis on fly ash, cement paste, mortar and concrete in their advance Microscopy & Microanalysis Facility at RMIT. I express my appreciation to their kind help. Besides, I would like to thank PT SIKA for cost-free supplying superplasticizer (Sikament NN) as an important admixture to produce concrete with low w/c ratio.

I also appreciate the assistance of the administrative staff at School of Civil, Chemical and Environmental Engineering of RMIT University and the library staff at the various universities. I wish to particularly acknowledge ever positive and efficient Marleen Manay, Sharon Taylor, and Joshua Monte who ably minded postgraduates' welfare and provided me with comfortable and conducive working environment at RMIT University during my candidature.

My family has been a dependable source of support --material and spiritual. My deepest gratitude is for my parents Bapak Badri and Ibu Sa'diyah Sungkar for their endless love and prayers; my wife, Qanitah Masykuroh, the first reader and editor of my thesis, for her love and encouragement. My son Aufa Sabila Rusyda and my daughter Nurinda Minata Ayuni, the source of joy in my broody moments, I am thankful for their understanding and bearing with a student father. I cannot conclude without mentioning the Indonesian communities in Melbourne Victoria who made my family and I have felt very much at home. I can only say 'Allah blesses them all'.

The last and the most important, all of the achievement is made possible only because of the mercy of Allah Lord of world, all praise is due to Allah Lord of world.

High performance concrete with high volume ultra fine fly ash reinforced with Basalt fibre

Abstract

The utilization of high strength concrete to support tall building construction industry is increasing. The increased use of high strength concrete consequently increases the Portland cement consumption. Moreover, the increase of the cement consumption causes more CO_2 emission from concrete industry which contributes to global warming. Hence, significant reduction in cement consumption by replacing part of cement using mineral admixture such as fly ash will be environmentally beneficial.

Fly ash is the most widely used mineral admixture offering improvement of concrete properties both for fresh concrete and hardened concrete. In addition, fly ash works as pozzolanic material, by binding the $Ca(OH)_2$ from cement hydration process to produce C-S-H gel which increases the concrete strength. It is found that one factor giving great influence on fly ash reactivity is the particle size and the particles smaller than 10 microns are more reasonably classified as pozzolanic reactive particles. Hence, this study deploys a micronizer, a jet mill using particle to particle impact mechanism to produce ultra fine fly ash.

At the first stage of this research, design of experiment method is used to examine the effect of low water/binder ratio and ultra fine fly ash content in compressive strength of mortar. In addition, the investigation on mortar strength development finds the appropriate use of saturated lime water in high volume ultra fine fly ash mortar which gives same compressive strength development as that in high strength OPC mortar and even higher at 56 days. The use of lime water as mixing water in high strength-high volume ultra fine fly ash mortar or concrete has not

been reported by any research although there have been some research on the use of lime in fly ash concrete to improve the properties of the concrete and the use of lime water as a requirement in mortar curing.

In addition to the use of ultra fine fly ash as cement replacement and the use of lime water as mixing water to produce high strength concrete, basalt fibre is also added in concrete mix proportion. The addition of basalt fibre is to balance one main weakness of high strength concrete i.e. the increase of relative brittleness as this new type of fibre has good resistance to chemical attack and good resistance in impact load and fire.

Hence, this research also examines the effect of type of fly ash, kind of mixing water and the utilization of basalt fibre on the strength of concrete by using design of experiment method. It is found that the brittleness of basalt fibre in alkali environment makes it inappropriate to use as concrete fibre. Also, the combination of high volume ultra fine fly ash with lime water as mixing water is found as the optimum mix proportion to produce high strength concrete which has similar concrete strength as ordinary portland cement concrete (OPC) starting at the concrete age of 28 days and beyond.

Moreover, the low porosity in the optimum concrete mix proportion enhances the durability by increasing $Ca(OH)_2$ substance to protect the concrete from carbonation. Besides the pore refinement effect of fly ash in concrete produce significantly low permeability to decrease sulfate absorption. The rapid chloride penetration test shows negligible criteria as the highest criteria for concrete resistance to chloride ingress.

List of publications

Solikin M., Setunge S., and Patnaikuni I., 2010, "*A Design Experiment of Mortar Compressive Strength With Different Water content and Different Ultra Fine Fly Ash Content*"**,** Proceeding of the 1st Makassar International Conference in Civil Engineering.

Solikin M., Setunge S., and Patnaikuni I., 2011, "The Influence of Lime Water as Mixing Water on The Compressive Strength Development of High Volume Ultra Fine Fly Ash Mortar"**,** ISEC-6, Zürich, June 21–26, 2011

Solikin M., Setunge S., and Patnaikuni I., 2011, "Experimental Design Analysis of Ultra Fine Fly Ash, Lime Water, and Basalt Fibre in Mix Proportion of High Volume Fly Ash Concrete", CUTSE 2011, Sarawak Malaysia November 8-9, 2011

Solikin M., Setunge S., and Patnaikuni I., 2011, "Effect of Water Binder Ratio and Ultra Fine Fly Ash Content on High Strength Mortar: An Experimental Design"**,** Journal of The South African Institution of Civil Engineering, (*submitted paper*).

Solikin M., Setunge S., and Patnaikuni I., 2011, "Experimental Design Analysis of Ultra Fine Fly Ash, Lime Water, and Basalt Fibre in Mix Proportion of High Volume Fly Ash Concrete"**,** PERTANIKA Journal of Science & Technology, (*accepted paper*; *This paper is scheduled for publication in Journal of Science and Technology in July 2013*).

Table of Contents

List of Tables

List of Figures

List of abbreviations

HVFA	: High volume fly ash
UFFA	: Ultra fine fly ash
OPC	: Ordinary portland cement
HRWR	: High range water reducer
w/c	: Water to cement ratio
w/b	: Water to binder ratio
C-S-H	: Calcium silicate hydrate
Ca OH	: Calcium hydroxide
f_m	: compressive strength
S_f	: flexural strength
f_{ct}	: modulus of rupture
AVPV	: apparent volume of permeable voids
A_s	: saturated absorption
A_i	: immersed absorption
RCPT	: Rapid chloride permeability test
SEM	: Scanning Electron Microscopy
EDAX	: Energy dispersive X-ray spectroscopy
µm	: micrometer
bf	: Basalt fibre
SF	: Steel fibre
A	: Aggregate
P	: Binder paste

1. Introduction

1.1. Background

1.1.1. High strength concrete as construction material

The origin of concrete which basically uses stones and gravel then binding with cementing material has been practiced for long time by the Egyptians, the Greeks, Etruscans, and Romans who used the mortar or concrete for their construction (Murdock et al., 1991). In the later development, the invention of modern cement by Joseph Aspdin in 1824 made concrete the main material in construction (Oficemen, 2011, Weizu, 2004).

Concrete has some advantages as main material for construction in comparison to the other construction materials (Mehta, 1986). It is the most readily available material everywhere and it possesses excellent resistance to water in comparison to wood and steel. Therefore, concrete has become a more durable material. In addition, the plastic consistency of fresh concrete makes it easier to be formed into a variety of shapes and sizes using prefabricated formwork.

The rapid development of construction industry has led to an increase in the demand for tall and long span concrete structures (Ashour et al., 1992), and this demand can be accomplished by high strength concrete, a type of concrete with compressive strength greater than 6,000 psi (41 MPa) (ACI 363R-92., 1997). It is due to the fact that high strength concrete can carry loads more efficiently than normal concrete, reduce the total amount of material needed and reduces overall cost of the structure (Cement and Concrete Basics, 2008).

Nevertheless, despite the benefit of using high strength concrete in construction, the increase of relative brittleness or the decrease of ductility of high strength concrete should be balanced. Some intensive research has been made to increase ductility of High Strength concrete by adding fibres in it (Ashour et al., 1992, Taylor et al., 1997). Fibre as discontinuous reinforcement will arrest the development or propagation of the micro cracks which are known to generate at early stage of the loading history. Different from plain concrete that fails immediately at the ultimate flexural strength, using fibre in concrete makes the load in concrete transferred from the concrete matrix to fibres after the first crack (Ramakrishnan, 2000).

There is a great variety of fibre materials which is commonly used in various sizes and shapes, such as steel fibres, glass fibres, synthetic (polymeric) fibres and carbon fibres (Nawy, 1996). Another type of fibre is basalt fibre which is made from basalt rocks through melting process which enables them to produce in the form of fibres. Previous research has shown that the basalt fibre is a good alternative system for strengthening material in concrete, particularly when moderate structural strengthening and high resistance to fire are needed (Sim et al., 2005).

It has been mentioned before that concrete has been widely used as main material for construction, and the development of concrete consumption has increased in tremendous quantity. In 1964 as reported by Brunauer (in Mehta, 2004) world annual concrete consumption was 3 billion tons. As the growth of world population, the consumption of concrete in 1986 increased to 4.5 billion tons per year (Mehta, 1986). Furthermore, it is estimated that with the world population of 7 billion in 2011 (UNFPA, 2011), the present concrete consumption is 21 billion tons per year (Mehta and Meryman, 2009). Nevertheless, in the view of environmental issue the production of concrete contributes 7% of world's CO_2 emission, a main contributor to the greenhouse gas effect and the global warming of the planet (Malhotra, 1999).

Regarding concrete ingredients, Portland cement produces the majority of CO_2 as it is responsible for 74% to 81% of CO_2 emission released to atmosphere from concrete (Flower and Sanjayan, 2007). Although typically the average use of Portland cement is only 15% by weight in concrete production (Wu and Naik, 2003), It is estimated that for every ton of cement used, it releases up to 0.99 tons CO_2 gas emission (Humphreys and Mahasenan, 2002).

As the CO_2 produced by Portland cement has a significant impact as a main contributor to the greenhouse gas effect and the global warming of the planet, in view of the environmental conservation, it is crucial to reduce the use of Portland cement in concrete production by using supplementary cementing materials. One of the supplementary cementitious materials for Portland cement which has now become the most widely used is fly ash (Kosmatka et al., 2003)

1.1.2. Fly ash in concrete

Fly ash as mineral admixture in concrete, is a by product of combustion of ground or powdered coal exhaust fumes of coal-fired power station (Nawy, 1996). The use of fly ash as a binder has proven to give many advantages for concrete properties, both in fresh concrete and hardened concrete (Oner et al., 2005).

Some of the advantages are increasing the workability, reducing bleeding, and retarding time set. In hardened concrete, fly ash contributes in continuing the hardened concrete's pozzolanic activity to gain higher strength at later ages, while the strength contribution rate of Portland cement decreases. Moreover, the durability of concrete incorporated with fly ash is better than that of normal concrete (Nawy, 1996).

The use of fly ash in concrete not only gives advantages to achieve high strength and high performance concrete, but also enables concrete to cope with the coal combustion waste problem. Hence, to give significant impact on reducing the CO_2 gas release to the atmosphere from concrete industry, it is necessary to support the use of concrete incorporated with large amounts of fly ash as a replacement for cement. Malhotra at CANMET (Canada Centre for Mineral and Energy Technology) in the 1980s introduced high volume fly ash (HVFA) concrete after conducting some researches on it. The HVFA concrete is the concrete with at least 50% of its Portland cement by mass replaced with ASTM class F or class C fly ash (Malhotra and Mehta, 2005). High-early strength of the concrete is obtained by reducing the water/ cementitious materials to 0.4 or less. Consequently, a high-range water reducer (superplasticizer) is used to increase the workability of concrete. By using high volume fly ash which contains large amount of fly ash, the concrete produced demonstrates the attributes of high-performance concrete (Bilodeau and Malhotra, 2000).

One of the factors giving great influence on fly ash reactivity is the particle size. The size of fly ash particles ranges from 1 – 150 µm and largely depends on the type of dust collection equipment (Siddique, 2008). Mehta has reported that a majority of the reactive particles in fly ash are actually less than 10 micron meters in diameter (Obla et al., 2003). In 1986 Butler and Mearing as reported in Xu (1997) found that fly ash particles having larger size than 10 µm mainly act as voids fillers in concrete, whereas the particles smaller than 10 microns are more reasonably classified as pozzolanic reactive particles.

Another factor that might influence in increasing pozzolanic reaction of fly ash is the present of lime in mix proportion of fly ash concrete. The previous research shows that the use of lime putty in fly ash concrete increased the durability properties of concrete (Mira P. et al., 2002). In addition, the use of lime powder in high volume fly ash concrete increased its compressive strength in comparison to high volume fly ash concrete without fly ash (Barbhuiya et al., 2009).

The use of fly ash as well as the use of ultra fine fly ash as concrete admixture in low or high content for producing high strength concrete has been widely used (Poon et al., 2000). However, despite the advantages it has, fly ash concrete usually demonstrates lower strength at early ages especially for high volume fly ash concrete in comparison to ordinary portland cement (OPC) concrete, although it shows higher strength at a longer period of time (Atis, 2003, Siddique, 2004). One method that has been used to get same early age strength concrete using fly ash as normal portland cement is by using elevated curing temperature (Elsageer et al., 2009).

The use of high volume fly ash and the use of ultra fine as concrete admixture for producing high strength concrete have been widely used. However with the slow strength development of fly ash concrete, this research examined the mechanical properties of high strength high volume ultra fine fly ash concrete to gain higher strength development at early age. The use of basalt fibre in concrete is also studied to increase the ductility of concrete.

1.2. Aim of the research

The previous literature review shows, that the use of ultra fine fly ash is beneficial in increasing strength of concrete, although it typically needs longer curing periods. Therefore this research will explore the feasibility of developing a high performance ultra fine fly ash concrete with replacement of 50% cement by ultra fine fly ash which has similar mechanical properties as ordinary Portland cement concrete. In order to get higher strength at early ages, lime water, a kind of alkaline solution was used as mixing water.

1.3. Research Objective

The objectives of this research are listed below:

a. Exploring the use of high volume ultra fine fly ash, lime water and basalt fibre to enhance concrete properties.
b. Understanding the mechanical properties of the proposed high volume ultra fine fly ash concrete.
c. Investigating the durability of the proposed high volume ultra fine fly ash concrete.
d. Analysing the microstructure of proposed materials using high volume fly ash concrete.

1.4. Scope of the thesis

To study the strength development and durability of high strength concrete with high volume ultra fine fly ash reinforced with basalt fibre, three factors are investigated which embrace type of fly ash, kind of mixing water and the utilization of basalt fibre. The type of fly ash factor comprises of the use of high volume raw fly ash and high volume ultra of ultra fine fly ash, whereas the kind of water consists of the use of lime water and tap water. Moreover, the addition of basalt fibre to improve the ductility of high strength concrete as well as high strength concrete without basalt fibre are also investigated.

Having established three factors to be analysed, experimental design, a statistical method, was used to prepare the mix proportion combination and to analyse the strength result of high performance high volume ultra fine fly ash concrete incorporated with basalt fibre. Furthermore, Minitab, a statistical software was used to conduct the experimental design.

This research commenced with a series of mortar experiments to establish design of experiment analysis on w/b ratio and fly ash content. In addition, strength development and water absorption of high volume ultra fine fly ash mortar using lime water as mixing water were also studied.

In the next stage, this research continued with the strength test of the concrete which embraces the tests on compressive strength, flexural strength and concrete modulus of elasticity. Whereas the durability tests of concrete consists of rapid chloride penetration test, carbonation test, and sulfate absorption test. In addition, the setting time and water absorption of concrete were also tested. Furthermore, to investigate the microstructure of concrete the Scanning Electron Microscopic (SEM) and Energy dispersive X-ray spectroscopy (EDAX) were used.

1.5. Outline of the thesis

The organization of this thesis is divided into seven chapters, as described below:

1.5.1. Chapter 1. Introduction

Introduction chapter briefly presents the importance of high strength concrete in supporting construction industry and the use of high volume fly ash concrete to enhance concrete's durability. In addition the aim, objectives and the scope of the research are also presented.

1.5.2. Chapter 2. Literature review

Chapter two presents the information from the existing literature to understand the role of fly ash in improving properties of concrete, the information about selected materials to produce high strength concrete and some durability criteria for high performance concrete.

1.5.3. Chapter 3. Materials and test methods

The next chapter with the subject of materials and test methods describes the materials which are used to produce high strength high volume ultra fine fly ash. In addition, the method of testing concrete properties and concrete durability are also presented.

1.5.4. Chapter 4. Mechanical properties of high volume ultra fine fly ash mortar

Chapter four explores the feasibility of using high volume ultra fine fly ash to produce high strength mortar. This chapter studies the effect of different w/binder ratio and ultra fine fly ash content on compressive strength of concrete. In addition, the discussion on the experiments on strength development of high volume ultra fine fly ash mortar and water absorption test of the mortar is also presented.

1.5.5. Chapter 5. Mechanical properties of high strength concrete with high volume ultra fine fly ash reinforced with basalt fibre.

Chapter five elaborates the effect of the type of fly ash, kind of mixing water and the utilization of basalt fibre in the mix proportion of high strength concrete. In addition, it also discusses the comparison of the mix proportion to that of control mix. Furthermore, a compressive strength analysis was conducted to find out the optimum mix proportion which focuses on those three factors. Besides, the chapter explores the analysis on modulus of elasticity test to all of mix proportion which is conducted after the optimum mix proportion is found.

1.5.6. Chapter 6. Durability test and microstructure analysis of high performance concrete with high volume ultra fine fly ash reinforced with basalt fibre.

Chapter 6 discusses the result of durability tests for all of concrete mix proportion focusing on the optimum mix proportion found in the earlier experiment discussed in chapter five. The durability tests comprise of water absorption test, carbonation test, sulfate resistance test and rapid chloride penetration test. Also, the chapter presents the discussion on the microstructure analysis of cement binder, hardened mortar and hardened concrete.

1.5.7. Chapter 7. Conclusion and recommendation for further research

The last chapter covers the finding of the research in regard to the use of high volume ultra fine fly ash to have same concrete properties as OPC concrete. In addition, it also presents some recommendations for further research in high volume ultra fine fly ash concrete.

2. Literature Review

2.1. Fly ash in concrete

Coal fly ash (fly ash) is a combustion by-product of pulverized coal in thermal power plants, which uses burning temperature of 1,300 – 1,400 ^{0}C. It is removed from the dust collection system of the exhaust gasses in coal fired power stations as very fine particles, predominantly spherical glassy, before they are discharge in to the atmosphere. The particle size of fly ash ranges from 1 – 150 µm, and the size of particles largely depends on the type of dust collection equipment, and the size of the fly ash particles is generally finer than that of Portland cement (Siddique, 2008).

The fly ash contains some major chemical substances i.e. Silica (SiO_2) around 5-25%, Alumina (Al_2O_3) about 10-30%, and ferric oxide (Fe_2O_3) about 5-25%. In addition, the fly ash also contains calcium oxide (CaO), magnesium oxide (MgO), sulphur trioxide (SO_3) and alkali oxide (Na_2O) (Nawy, 1996). Based on the major chemical contents in fly ash, there are three types of fly ash i.e. class F, class N, and class C fly ash.

In class F and class N fly ash, the total minimum amount of SiO_2, Al_2O_3, and Fe_2O_3 is 70%, whereas in class C the total amount of SiO_2, Al_2O_3, and Fe_2O_3 is between 50% and 70% (ASTM C 618-03., 2003). The class F and class N fly ashes have low calcium oxide (CaO) content whereas the class C fly ash has high calcium oxide content (more than 10% and often 15-20%).

Table 2.1: Chemical content for different class of fly ash (ASTM C 618-03., 2003)

	Class		
	N	F	C
Silicon dioxide (SiO_2) plus aluminium oxide (Al_2O_3) plus iron oxide (Fe_2O_3), min %	70.0	70.0	50.0
Sulphur trioxide (SO_3), max %	4.0	5.0	5.0
Moisture content, max %	3.0	3.0	3.0
Loss on ignition, max %	10.0	6.0[A]	6.0

[A]The use of class F pozzolan containing up to 12% loss on ignition may be approved by the user if either acceptable performance records or laboratory test result are made available.

Class C fly ash is produced from burning of sub-bituminous coal whereas class F fly ash is produced from burning of bituminous coal. As a result of higher calcium oxide content, class C fly ash has some cementitious properties and pozolanic properties while class F fly ash only has pozzolanic properties (Ramachandran, 1995).

Studies on fly ash in Portland cement concrete began in 1930s when the quantity of fly ash which mainly comes from coal-burning electric power plant became available as pozolanic materials. In 1937, R.E. Davis from the University of California published result of research on fly ash and the work served as foundation for early specifications, methods of testing, and use of fly ash in concrete (ACI 226-3R-87., 1987).

By the year 2000 world production of fly ash was estimated as 600 million tons per year (Bilodeau and Malhotra, 2000). Based on the world survey, only 16.1% or approximately 90 million tons was utilized. Nevertheless, the total amount of fly ash used in concrete was about 27.9 million tons, consisting of 2.8 million tons used as cement raw materials, 7.6 million tons in blended cement, and 17.5 million tons for cement replacement (Lohtia and Joshi, 1995).

2.1.1. Fly ash Mechanism as cementitious material

As supplement material for cement, fly ash goes through some processes to become cementitious material. This section will explore the mechanism in which fly ash contributes to the strength development of concrete.

The process starts with hydration of cement, a chemical reaction between water and cement to produce cement paste, in which the cement paste contains about 70% of C-S-H (Calcium Silicate Hydrate), 20% of calcium hydroxide ($Ca(OH)_2$), 7% sulpho-aluminate and 3% of secondary phases (Oner et al., 2005). The C-S-H in cement paste is the substance which gives the strength of the concrete whereas $Ca(OH)_2$ in hydrated cement paste gives negative effect on concrete quality as the $Ca(OH)_2$ is water soluble and has low strength.

While $Ca(OH)_2$ in hydrated cement paste gives negative effect on concrete quality, the presence of fly ash in concrete with high content of Silica (SiO_2) gives positive contribution to cement paste properties as it would bind the $Ca(OH)_2$ to produce C-S-H gel and lead to the increase in the concrete strength. The difference of cement hydration reaction between the no-presence and presence of fly ash in concrete could be seen below (Oner et al., 2005):

<u>Cement hydration:</u>

Cement ($C_3S;C_2S$) + H_2O $\rightarrow$ CSH-gel + $Ca(OH)_2$

<u>Fly ash reaction:</u>

$Ca(OH)_2$ + SiO_2 $\rightarrow$ CSH-gel

From the chemical reaction above, it could be understood that fly ash works after cement hydration that produces $Ca(OH)_2$. It makes the strength of fly ash concrete lower than that of ordinary portland cement (OPC) at early ages (Atis, 2003). However, after longer period of curing, the strength of fly ash concrete is possible to reach the same strength as OPC concrete.

As silica in fly ash needs $Ca(OH)_2$ to produce C-S-H gel, Mira P. et al. (2002) investigated the influence of lime in mix proportion of fly ash. The lime putty addition of 25% of cementitious material did not show significant difference on compressive strength development of fly ash concrete compared to the fly ash concrete without the lime, however the concrete stability and concrete durability improved significantly. In addition, Barbhuiya et al. (2009) who used 5% hydrated lime as fly ash replacement in high volume fly ash concrete confirm significant increase of compressive strength development compared to high volume fly ash concrete without hydrated lime substitution of fly ash.

In terms of the rate of reaction, temperature gives considerable effect on it, generally the higher the temperature the faster the rate of chemical reaction (Alten, 1999, Baliga K. B. et al., 2010). Therefore Elsageer, et al. (2009) conducted research on the effect of curing temperature on the strength development of high volume fly ash. By using fly ash content of 45% as cement replacement and using elevated curing temperature of $50^{o}C$, it was found that fly ash concrete strength development is higher compared to OPC concrete and lower content of fly ash for the same curing method.

In addition to the reaction that fly ash undergoes to become cementitious material, the size, the shape, the texture of the particles and the mineralogical characteristics of fly ash determine mechanism of its influence on the concrete properties both for fresh concrete and hardened concrete (Malhotra and Mehta, 2005). Hence, the use of different source of fly ash will give different effect on concrete.

2.1.2. Ultra fine fly ash

One of the factors greatly influencing fly ash reactivity is the particle size. Fly ash particles have size distribution ranges from slightly greater than 150 micro-meters to submicron size (Obla et al., 2003). In regard to pozzolanic activity, the number of particles less than 10 µm will proportionally influence the pozzolanic activity of fly ash whereas particles larger than 45 µm show little or no pozzolanic property (Malhotra and mehta, 1996). Mehta (1985) also reported that the majority of the reactive particles in fly ash are actually less than 10 micro-meters in diameter.

Furthermore, In 1986, Butler and Mearing as reported by Xu (1997) found that fly ash particles in the range of 10 to 50 µm mainly act as voids fillers in concrete, whereas the particles smaller than 10 µm are more reasonably classified as pozzolanic reactive particles.

Ultra fine fly ash can be produced by grinding raw fly ash or by using selective classification using air classifiers. In the past, both technique have typically been cost prohibitive, however; currently the technic has been becoming commercially available to manufacture ultra fine fly ash (UFFA) (Kevin D. Copeland et al., 2001).

Another technique to produce ultra fine fly ash is by utilizing selective classification in which a proprietary separation system that includes selective air classification is used. The system could manufacture ultra fine fly ash with an average particle size of 3 micro-meters with 90% of the particle size less than 7 micro-meters (Kevin D. Copeland et al., 2001). The finding of the study shows that the addition of either 12% of ultra fine fly ash by weight of cement or to the addition of 8% of silica fume gave the same improvement of concrete compressive strength at the age of 28 days. Nevertheless, considering that the silica fume is more expensive in comparison to the price of ultra fine fly ash, the use of ultra fine fly ash would give financial efficiency. Moreover, ultra fine fly ash increases concrete durability based on the rapid chloride penetration resistance test, bulk diffusion test, alkali silica reaction test and sulfate resistance test.

In grinding of raw fly ash, Sengul et al. (2005) used a ball mill type of grinder and the technique can increase the surface area of raw fly ash from 222 m^2/kg to 604 m^2/kg. The increase of the fineness demonstrates the increase of the pozzolanic reactivity of fly ash which can be seen by the small reduction of the compressive strength of concrete and the increase of the chloride penetration resistance. While replacing the cement content of 50% with the fine fly ash decreased the concrete's compressive strength by 25%, the replacement significantly increased the durability of the concrete which resulted from the increase of rapid chloride penetration resistance.

In addition, Baoju et. al. (2001) conducted a research which used 25 - 50% ultra fine fly ash as cement replacement with the surface area of the ultra fine fly ash was 600 m^2/kg. The result of the research shows that the compressive strength of concrete would decrease when the use of ultra fine fly ash is increased. To cope with the strength decrease problem, longer period of curing on concrete with 50% replacement of cement with ultra fine fly ash is needed to increase its compressive strength to reach more than 50 MPa which meets the criteria of high strength concrete.

Moreover, processing raw fly ash to become ultra fine fly ash with major particle size of 3 microns as mineral admixture, will improve the concrete performance i.e. increasing pozzolan reactivity, reducing water demand, and becoming alternative for expensive high-reactive pozzolanic material such as silica fume (Obla et al., 2003).

2.1.3. High volume fly ash.

The term of high volume fly ash (HVFA) concrete is firstly introduced by Malhotra at CANMET in the 1980s. The HVFA concrete is the concrete with at least 50% of the Portland cement by mass is replaced with ASTM class F or class C fly ash (Malhotra and Mehta, 2005). High-early strength is obtained by reducing the water/ cementitious materials to less than 0.4. Consequent to the use of low water/cement ratio, a high-range water reducer (superplasticizer) is used to make desired slump, values ranging from 150 to 200 mm.

Although high volume fly ash concrete contains large amount of fly ash, the concrete produced demonstrates the attributes of high-performance concrete (Bilodeau and Malhotra, 2000). The HVFA concrete has excellent workability as the result of the excessive volume of cement and fly ash in the concrete mix in comparison to OPC concrete. The increased volume produces larger cementitious paste volume, hence better workability (Nawy, 1996).

The superplasticizer is necessary in high volume fly ash when low water content is used (the ratio of water/binder is about 0.4). The dosage needed depends on the required slump and is generally about 1.5% of the total cementitious materials (Nawy, 1996).

Besides the excellent workability, the HVFA concrete also shows low heat-of-hydration, adequate early-age strength and very high later-age strength, low drying shrinkage, and excellent durability characteristics that are essential for sustainability enhancement of modern concrete construction (Nawy, 1996).

Moreover, the large amount of fly ash use in concrete would become an ideal solution in reducing of CO_2 emission and solve the waste problem of coal fired power stations. In addition the high volume fly ash concrete system is environmentally friendly and the concrete produced demonstrates the attributes of high-performance concrete (Bilodeau and Malhotra, 2000).

There have been some civil engineering structures which are built using the high volume fly ash concrete, as reported by Malhotra and Mehta (2005). The structures are: Concrete block for communication satellite, Ottawa, Canada (1987); Park Lane Hotel, Halifax, Canada (1988); Polypropylene Fibre Reinforced High-Volume Fly Ash shot-crete, Nova Scotia, Canada (1992); Seismic Rehabilitation Of Barker Hall, University Of California at Berkeley, U.S.A. (2001); and Residential Buildings in San Francisco (1999).

2.1.4. Effect of fly ash on the properties of concrete

It has been mentioned that the use of fly ash in concrete will be beneficial for fresh concrete to increase the workability, to reduce bleeding and to retard time set. In hardened concrete the fly ash continues its pozzolanic activity to gain higher strength at later ages, while the strength contribution rate of Portland cement decreases. The durability of concrete incorporated with fly ash is better than that of normal concrete (Nawy, 1996). This section will discuss the effects of fly ash on the properties of concrete which embrace the workability, the bleeding, the time set, the strength and the durability of concrete.

The increase of workability of fly ash concrete can be seen from slump test result (Alvarez et al., 1988). The increase of workability is caused by the spherical shapes of the fly ash that reduces the friction between cement and aggregates and results in an increase in the workability of fresh concrete (Sata et al., 2007). Besides the increase of workability, as the utilization of fly ash in concrete tends to increase cohesion, pumpability and less tendency to cause segregation; fresh properties of fly ash concrete are preferred in application which requires pumping and spray of concrete (Sanjayan and Patnaikuni, 2004).

The bleeding of fresh fly ash concrete depends on the original fineness of fly ash and the water/cementitious ratio (w/c) of the concrete (Bouzoubaâ et al., 1999). Similarly, as reported by Cheng and Osbeck the bleeding of concrete decreases significantly along with the increase in the fineness of the fly ash (Bouzoubaâ et al., 1999). However, when very low w/c ratio is used, the bleeding of high-volume fly ash concrete ranges from very low to negligible (Bilodeau and Malhotra, 2000). In addition, fly ash generally reduces bleeding as it provides greater volume of fines particles and needs lower water content in the mixture (Nawy, 1996).

The setting time of cement paste containing fly ash which is determined by the vicat test showed the existence of retardation in the setting time both for initial and final setting (Bentz and Ferraris, 2010). The longer setting time of fly ash concrete is due to the decrease of cement content and the slow reaction process of the fly ash and the large amounts of superplasticizer used (Bilodeau and

Malhotra, 2000). Besides, the increase of retardation is related to the increase of fly ash content (Alvarez et al., 1988).

The increase of the quantity of fly ash used in concrete will increase the concrete compressive strength until it reaches its optimum content, and beyond that point, the strength of concrete starts to decrease with further addition of fly ash (Oner et al., 2005). Although the use of fly ash can result in a lower compressive strength at early ages, with the continued pozzolanic activity of the fly ash, higher strength will reach at later ages (Nawy, 1996).

As fly ash concrete needs longer period to complete its reaction, the curing of the concrete becomes very important to maintain the pozzolanic reactivity of fly ash. The strength of the concrete containing fly ash is more sensitive to poor curing compared to the concrete without fly ash. The sensitivity increases along with the increased amounts of fly ash used in the mixtures (Ramezanianpur and Malhotra, 1995).

The modulus of elasticity of fly ash concrete can be obtained from its tangent slope of stress-strain diagram and the modulus of elasticity of concrete containing fly ash particularly at early ages, is slightly higher in comparison to OPC concrete (Nawy, 1996). In addition, when high volume fly ash is used in concrete, higher amount of fly ash used will reduce the modulus of elasticity of concrete and lead to the increase of the concrete brittleness (Sengul et al., 2005). However, the use of low content of fine fly ash potentially increases concrete stiffness i.e. tensile strength and modulus elasticity (Haque and Kayali, 1998).

In regard to the durability of fly ash concrete, as summarized by Bouzoubaa et al. (1999) previous researchers have revealed that the use of fly ash increases concrete resistance against alkali aggregate reaction, resistance to sulfate attack, resistance to chloride-ion penetration, resistance to freezing and thawing cycles and Deicing salt-scaling resistance.

2.2. High strength and high performance concrete

Based on American Concrete Institute, High strength concrete is concrete with a compressive strength greater than 6,000 psi (41 MPa) (ACI 363R-92., 1997). High strength concrete is needed where the reduction of structure's dead weight is important or where an architectural consideration is needed for small support elements. High strength concrete carries loads more efficiently than normal concrete, reduces the total amount of material needed and reduces overall cost of the structure as well (Cement and Concrete Basics, 2008). High strength concrete is commonly used for high-rise building constructions such as the Twin Tower PETRONAS in Malaysia which used 80 MPa concrete strength, the Taipei 101 tower which used 69 MPa concrete strength and the Burj of Dubai which used 80 MPa concrete strength (Subramanian, 2010).

High strength concrete is usually made using stringent requirements of material and the use of low w/c ratio is essentially considered (ACI 363R-92., 1997). The combination of both factors in concrete mix proportion not only influences the high strength result of concrete but also increases some characteristic performances of concrete resulting in higher flow-ability, higher elastic modulus, higher flexural strength, lower permeability, improved abrasion resistance and better durability (Aïtcin, 2004). Hence, the term 'high performance concrete' might also be used to describe the advanced properties of the high strength concrete. However, eventually the high performance attributes are not only found in high strength concrete (Neville and Aitcin, 1998).

2.3.1. Materials for high strength concrete

Generally, high strength concrete is produced from the mixing of strong aggregate, a higher Portland cement content, low water/cementitious ratio, and selected admixture such as water reducing admixture, superplasticizers, polymers, blast furnace slag, or silica fume (Nawy, 1996). Cement in concrete is manufactured by mixing the raw major component, i.e. limestone, clay and marl (calcium carbonate) with addition of some minor components such as silica sand and iron ore then heated in rotary kiln at 1,450 ^{o}C to form the Portland cement pellet (Heidelberg Cement, 2008). The cement reaction with water is a complex chemical reaction named as hydration of cement which forms the adhesive property for all of concrete components (Mehta, 1986).

For producing high strength concrete, the cement content vary ranging from 330 kg/m^3 – 620 kg/m^3 with the higher cement content tends to make the compressive strength higher (Alves et al., 2004, Ozbay et al., 2009). In addition, the different result of same cement content to its compressive strength is influenced by some factors in concrete production, for instance: water to cementitious materials ratio, water content, percentage of fine aggregate to total aggregate, and admixture content.

In regard to the use of aggregates in concrete, the aggregates constitute the bulk of the finished concrete as they occupy 60% - 80% of the volume of the concrete (Nawy, 1996). Since the aggregate does not engage in chemical reaction of concrete, it is frequently looked upon as inert filler (Mehta and Monteiro, 2006).

The research shows that aggregate has influence on strength, dimensional stability, durability, workability and cost of the concrete as well.

Moreover, as the colloidal gel or cement paste is merely a result from reaction between water and cement, it is important to be concerned about water/ cement ratio or the water binder ratio used. Excessive water leaves an uneven honeycombed skeleton in the finished product, while too little water prevents complete chemical reaction with the cement and leaves powder voids in concrete. Both excessive and too little water for cement hydration will decrease concrete strength (Nawy, 1996).

High strength concrete needs low water-cement ratio, because concrete strength is significantly increased by the decrease of the water/cement ratio. The suggested water/cement ratio to produce high strength concrete incorporated with silica fume is 0.35 (Behnood and Ziari, 2008) and using the low w/binder ratio leads to high performance concrete with good result. As guidance, to produce high performance concrete, a water/cement ratio of 0.4 can be used as boundary limit (Aïtcin, 2004). The decrease of water/ cement ratio will have affect in decreasing concrete workability, therefore some admixture is added, which preferably is in liquid form such as superplasticizers to increase concrete workability by increasing the slump of the mix (Nawy, 1996).

Furthermore it is important to note on the limitation of lowering water/cement ratio to increase compressive strength of concrete which leads to the increase of superplasticizers use (Poon et al., 2000, Ting and Patnaikuni, 1992). This limitation is resulted from the finding that the use of lowering water/cement ratio only increases the compressive strength of the paste and decreases the porosity of concrete, but it does not further improve the concrete strength and the durability properties.

2.3.2. Basalt fibre

The benefit of using high strength concrete in construction has a down side, namely increase of relative brittleness or reduction of ductility of high strength concrete which should be balanced, alternatively by adding fibres in it to increase the ductility (Taylor et al., 1997).

The idea of using fibres in concrete comes from the Egyptian and Babylonian eras where straws are usually used to reinforce bricks (Nawy, 1996). At later development, modern research about concrete fibre commenced in the early 1960s with primarily using steel fibre.

One of the recent types of fibres is basalt fibre that is made from basalt rocks, a natural material which comes from volcanic rocks by melting basalt rock at high temperature (1,300℃ - 1,700℃) and spin it in the form of fine fibres (Rusakov, ---). The patent of basalt fibre was obtained in 1923 when Paul Dhé, from Paris got the US patent for extruding filaments from basalt. In 1950s to 1960s some researches about basalt fibre was conducted in Russia and Czech Republic. Further intensive researches and development effort took place in the North-West of the USA in 1960/1970s which has large basalt deposits. At the beginning, this technology was only used in military and aerospace applications. The basalt fibre technology was kept secret and was the object of little publication, however after perestroika in 1990/92 it was allowed to be used for the civilian field (Jean-Marie, 2003).

Basalt fibre has some good mechanical properties that makes it beneficial for concrete structures. For instance, basalt fibres have better tensile strength than E-glass fibres, greater failure strain than carbon fibres, and good resistance to chemical attack, impact load and fire (Mingchao et al., 2008, Sim et al., 2005). The comparison of the mechanical properties of some fibres is described in the **Table 2.2**.

Table 2.2: Mechanical properties of some fibres

Name Fibre	Basalt Fibre[1)]	Steel Fibre [2)]	Carbon Fibre [3)]	Glass Fibre [4)]	Synthetic Fibre [5)]
1. Tensile strength (MPa)	1,000	400.0 - 1,100.0	3,500.0	3,100.0	550.0
2. Ultimate elongation (%)	3.0	18.0	2.0	4.7	4.0
2. Elastic modulus (GPa)	70.0	200.0	230.0	68.0	10.0
3. Density (kg/m^3)	2,670.0	7,850.0	1,780.0	2,680.0	900.0

[1)] (K et al., [no date], Pavlovski, 2007)
[2)] (Cachim et al., 2002, Topc¸u and Canbaz, 2007)
[3)] (Chen and Liu, 2008)
[4)] (GHUGAL and DESHMUKH, 2006, K et al., [no date])
[5)] (Shogun product data sheet, [no date], Topc¸u and Canbaz, 2007)

Although using basalt fibres in concrete mix design will decrease the compressive strength and splitting tensile strength test of concrete, but it will give advantage for concrete beams. The addition 1% of basalt fibre presented higher ultimate load and larger displacement before failure for concrete beams (Dias and Thaumaturgo, 2005). The basalt fibres are more efficient in strengthening concrete beams and they are tougher in comparison to the concretes without basalt fibres.

2.3. Durability of concrete

According to ACI committee 201, durability of Portland cement concrete is defined as its ability to resist weathering action, chemical attack, abrasion or any other process of deterioration; that is durable concrete will retain its original form, quality, and serviceability when exposed to its environment (ACI 201.2R-01, 2001). Durability can be explained as a long service life, even though actually no material is naturally durable because of the interaction of its microstructure with environment. Consequently the properties of materials change along with time. A material is assumed to reach its end of service life when the continuing uses of the material will be either unsafe or uneconomical (Mehta, 1986).

The deterioration of concrete that diminishes its durability occurs after the concrete is in contact with the environment, and the deterioration usually refers to the following deterioration mechanism: Chloride ion deterioration, carbonation-induced reinforcement corrosion, sulfate attack, and salt-scaling (Al-Tamimi et al., 1998).

2.3.1. Chloride ion penetration

Chloride ion penetration is the most devastating problem related to normal concrete exposed to environment. Chloride ion in adequate amount will modify the microstructure of concrete and seriously damage the concrete because when it reaches the steel reinforcement it will depassivate steel reinforcement and cause corrosion to occur, even under the conditions of high pH characteristic of concrete pore solutions (Aïtcin, 2004, Page, 2007).

The reaction of chloride with un-hydrated tricalcium aluminate, a substance in cement composition, will produce an expansive product which is called the Friedel's salt (Islam et al., 2010, Mancio et al., 2010). This salt has a property of low to medium expansion. Also, the formation of excess calcium chloride, which may leach out, results in the increasing permeability of concrete.

$$CaCl_2 + 3CaO{\cdot}Al_2O_3 + nH_2O \rightarrow 3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O$$

Chloride + tricalcium aluminate → friedel salt

The process of chloride ion transport from sea water or de-icing salts into concrete is a complex process which involves several mechanisms i.e. diffusion, capillary suction and convection and its transport is affected by several parameters (Elakneswaran et al., 2009).

The most important variable which relates to the chloride ion ingress is the porosity of concrete in which lower porosity leads to the decrease of chloride ion ingress. Hence, low w/c ratio and better concrete compaction become the key factor to reduce concrete porosity. In addition the use of pozzolanic material such as silica fume or fly ash will reduce porosity (Collepardi and Biagini, 1989, Collepardi et al., 1972).

2.3.2. Carbonation of concrete

Having discussed the Chloride ion penetration, the other deterioration of concrete is called carbonation will be considered. Carbonation of concrete is the reaction between concrete and CO_2 in the atmosphere which reduces concrete's pH to less than 9. The decrease of concrete's pH leads to depassivation of steel reinforcement and cause corrosion to occur (Papadakis et al., 1989, RILEM CPC-18, 1984) . This type of deterioration especially happens in urban environments with high concentration of CO_2 in the atmosphere.

The CO_2 reacts with $Ca(OH)_2$, a product of concrete hydration, to produce $CaCO_3$ which tend to lower the pH. The reaction needs water as medium of reaction, as an be seen in the following chemical reaction (Formtex, 2003, Papadakis et al., 1989).

$$CO_2 + H_2O \rightarrow H_2CO_3$$

$$Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3$$

With the same concentration of CO_2 coming from the atmosphere, the higher $Ca(OH)_2$ in concrete would be beneficial to lengthen the period for CO_2 to ingress into the concrete.

Regarding with the utilization of fly ash in concrete, carbonation becomes a potential problem in high volume fly ash concrete as accepted by among researchers as it is agreed that the carbonation depth of concrete increases when the compaction of fresh concrete decreases, the permeability increases, the strength decreases, the w/c ratio increases, the cement content decreases and the fly ash content increases (Berry and Malhotra, 1986, Burden, 2006, Gebauer, 1982, Roberts, 1981). Therefore, to improve resistance to carbonation in high volume fly ash concrete, this research studied the utilization of ultra fine and low w/binder ratio to produce durable concrete.

2.3.3. Sulfate attack

Another concrete deterioration is sulfate attack which is caused by a reaction of hardened concrete substances with sulfate ion from internal sources or external sources (Skalny et al., 2002) The laboratory experiment of concrete carbonation shows a decomposition reaction of primary cement hydration product (calcium hydroxide and calcium-silicate hydrate) to form gypsum which subsequently will produce ettringite where the growing of the crystal formation makes expansion, cracking, and loss of strength and loss of adhesion in concrete (Mehta, 1992).

The formation of ettringite can be described using following chemical reaction (Cohen and Bentur, 1988):

$CH + N\bar{S} + 2H \rightarrow C\bar{S}H_2 + NH$

($N\bar{S}$ is Sodium sulfate; CH is calcium hydroxide; $C\bar{S}H_2$ is gypsum)

Further reaction between gypsum with cement hydration product will create ettringite.

$C_4AH_{13} + 3C\bar{S}H_2 + 14H \rightarrow C_6A\bar{S}_3H_{32} + CH$

$C_3A + 3C\bar{S}H_2 + 26H \rightarrow C_6A\bar{S}_3H_{32}$

(C_4AH_{13} is hydrated calcium aluminates; C_3A is un-hydrated tricalcium aluminates; $C_6A\bar{S}_3H_{32}$ is ettringite)

In addition for permeable concrete which is exposed to sodium sulfate salt solution, the sulfate attack mechanism is not a chemical reaction, but it is considered as physical action (Mehta, 1992). The mechanism starts when the solution rises to the surface of concrete by capillary action and then, as a result of surface evaporation the salt becomes supersaturated and the expansion of crystal grows generating large enough pressure to cause cracking.

The source of sulfate ion might be derived from internal sources which are caused by excessive sulfate in clinker and cement and external sources caused by sulfate chemical substance such as Na_2SO_4, K_2SO_4, and $CaSO_4$.

The internal sulfate ion mainly comes from cement and the external sulfate source mainly comes from ground water. Regardless of the source, the sulfate attack is usually a result of poor concrete casting practice which leads to permeable concrete and enables sulfate ion to penetrate porous concrete through its open pore structure.

The investigations performed at CANMET indicates that fly ash concrete has excellent durability in relation to frost action, has very low permeability to chloride ions diffusion and shows no adverse expansion when highly reactive aggregates are incorporated into the concrete (Malhotra, 1990). Moreover, fly ash concrete significantly lowers weight losses, increases efficiency of abrasion resistance, increases resisting of wet and dry repetition test, and increases water repellence (Dinakar et al., 2008, Yoona et al., 2002).

2.4. Summary of chapter 2

The literature study in chapter two explores some significant points of review to be noted here i.e:

a. There are some methods to enhance the properties of high volume fly ash concrete to produce high strength concrete :
    - By increasing pozzolanic reaction rate which can be achieved by using small particles size of fly ash (less than 10 microns).
    - By increasing alkali substance in the high volume fly ash concrete that will react with high content of silica.
    - By using basalt fibre which has good resistance to chemical attack, impact load and fire as strengthening material to enhance the ductility of high strength concrete.

b. There is a mechanism of deterioration of concrete durability when the concrete is exposed to chloride environment, carbon in the atmosphere and sulfate absorption.

c. The use of fly ash as cement replacement is beneficial in increasing some durability properties of concrete.

Having reviewed the factors which can increase the strength properties of high strength concrete and the mechanism of the deterioration durability test for high performance concrete, the next chapter will explore the materials and test methods for high performance concrete focusing on the use of high volume ultra fine fly ash, lime water as mixing water and basalt fibre as concrete reinforcement.

3. Materials and Test Methods

3.1. Overview

Based on the literature review, there are three factors considered as the influencing factors in increasing properties of high volume fly ash concrete, i.e. the utilization of ultra fine fly ash as cement replacement, the increase of alkali substance in high volume fly ash and the deployment of basalt fibre as strengthening material which will increase concrete's ductility. The use of fly ash in concrete has dual advantages in supporting green environment as well as improving some of concrete properties. The high volume fly ash reduces the waste from the combustion of coal-fired power station and reduces CO_2 emissions due to the utilization of Portland cement in concrete industry. In addition, despite the slower strength development of high volume fly ash concrete in comparison to OPC concrete, the use of fly ash as a binder has proven to give many advantages for concrete properties, both in fresh concrete and hardened concrete.

The literature review indicated that ultra fine fly ash will increase reactivity of fly ash considering that the particle size is a great influencing factor in fly ash reactivity. The former research shows fly ash particles in the range of 10 to 50 µm mainly act as voids fillers in concrete, whereas the particles smaller than 10 microns can be more reasonably classified as pozzolanic reactive particles. Hence, in this research it was decided to use ultra fine fly ash to improve the strength of high volume fly ash concrete.

The ultra fine fly ash in this research was produced by grinding the raw fly ash using a micronizer, a jet mill machine which deploys particle to particle impact mechanism. In addition, the investigation of high volume raw fly ash concrete properties is also conducted as comparison to the use of ultra fine fly ash concrete.

It is well established that high strength concrete offers many advantages in structural property. However one of the disadvantages noted is the low ductility. Therefore, the use of basalt fibre as a strengthening material in high strength concrete was studied in the work presented here.

Based on literature review, the high strength concrete with the high volume fly ash can be obtained by using low water content, increasing the reactivity of the fly ash and using smaller size of aggregate. This research uses ultra fine fly ash to increase the reactivity of fly ash. In addition, the use of lime water as mixing water to possibly increase the reactivity of fly ash by increasing alkali substance in high volume ultra fine fly ash was also studied. Moreover, as a requirement of low water content in the mix of high volume fly ash concrete, a high range water reducer or superplasticizer was also utilized.

This research investigated 3 factors to produce high strength concrete i.e. the use of high volume ultra fine fly ash, the use of basalt fibre as strengthening material and the use of lime water to increase alkali substance in high volume ultra fine fly ash concrete. In order to establish the influence of the three factors on concrete strength it was decided to adopt a statistical technique to design the experiment (Montgomery, 2009). Design of experiment, a statistical method, was used to prepare the mix proportion combination and to analyse the strength result of high strength-high performance of high volume ultra fine fly ash concrete incorporated with basalt fibre.

To study the possibility of using high volume ultra fine fly ash as cement replacement to produce high strength concrete, this research program was commenced with studying mix proportion of high volume ultra fine fly ash mortar to obtain a high compressive strength test result. The result of mortar mix proportion for high volume ultra fine fly ash mortar were used as basis to prepare mix proportion of high strength and high performance of high volume ultra fine fly ash concrete incorporated with basalt fibre.

As high performance concrete not only depends on its strength but also on other mechanical properties, the mechanical properties of high performance high volume ultra fine fly ash concrete incorporated with basalt fibre were also investigated i.e. properties of fresh concrete, properties of hardened concrete and the durability of concrete. Test for fresh concrete consists of time setting and slump test. In addition, test for hardened concrete consists of water absorption, compressive strength, modulus of rupture, and static modulus of elasticity. In addition to the hardened concrete tests, the durability tests of concrete were also conducted which consisted of rapid chloride penetration test, sulfate resistance test and carbonation test.

3.2. Materials and specimens preparation

Concrete is made of aggregates which are bound with cement paste which is a product from cement hydration, a reaction between cement and water. Some admixtures can be used to meet the requirements of concrete properties e.g. to increase workability, to retard time set, to achieve high compressive strength, and to increase its durability (Ramachandran, 1995).

The aggregate for concrete consists of coarse aggregate and fine aggregate. The fine aggregate has a grading of size between 150 µm to 4.75 mm whereas coarse aggregate has larger size than fine aggregate, up to the size of 63 mm (ASTM C33-03, 2003).

To produce high strength concrete, it is very important to select the materials. In this study, the aggregate used is coarse aggregate which has maximum size of 10 mm. This use is based on the result investigated in previous research which showed that the use of small coarse aggregate leads to the increase of concrete strength in comparison to the larger aggregate as smaller aggregate is stronger than the larger ones. In addition, the low strength of concrete using larger aggregate is caused by the bigger size of aggregate make the transition zone becomes larger and more vary (Aïtcin P.C, 1988, Aïtcin, 2004).

In addition to the aggregate size, since the cement matrix becomes a granular skeleton of the aggregate, the lower the distance between two adjacent coarse aggregate particles, the higher the matrix strength (Larrard and Belloc, 1997).

Furthermore, crushed sand was used as a fine aggregate. The material properties of aggregate used in this experiment are shown in **Table 3.1**.

Table 3.1: Material properties of aggregate

Properties	Sand	Coarse Aggregate
Density	2.60	2.89
Moisture content	1.0%	0.2%
Water absorption	0.8%	0.4%

3.2.1. Ultra fine Fly ash

For this research, the binder in concrete mix design consists of Portland cement and fly ash. Type I of Portland cement was used as cement and the fly ash as pozzolanic material came from Tarong power plant. The Tarong fly ash was classified as Low calcium fly ash or ASTM class F fly ash as the sum of SiO_3 + Al_2O_3 + Fe_2O_3 is more than 70%, and also the CaO content of the fly ash is less than 10%. The chemical composition of Tarong fly ash is shown in **Table 3.2**.

Table 3.2: Chemical Properties of Tarong fly ash (mass %)

	Tarong fly ash *)	ASTM Class F**)
SiO_2	65.90	The sum of SiO_3 + Al_2O_3 + Fe_2O_3 min 70%
Al_2O_3	28.89	
Fe_2O_3	0.38	
TiO_2	1.97	
MnO	0.00	
MgO	0.15	
CaO	0.06	
Na_2O	0.05	
K_2O	0.26	
P_2O_5	0.08	
SO_3	0.03	Max, 5%
LOI	1.24	Max, 6 %

*) (Sofi et al., 2007)

**) (ASTM-C-618-03, 2003)

Figure 3.1: Tarong fly ash

Before the fly ash was used as binder in concrete as cement replacement, the raw fly ash was ground in micronizer to obtain the ultra fine fly ash (UFFA). The micronizer is a jet mill, using compressed air or gas to make high speed rotation of the particles in grinding chamber which further leads the material to particle-on-particle impact (Sturtevant, 2000). The grinding chamber of the micronizer has diameter of 2 inches, named as Micronizer OM2. The grinding process utilized a screw feeder to maintain the constant feeding to the grinding chamber. From the grinding mechanism in micronizer it is possible to increase the fineness of the material ranging from 0.5 to 45 microns

The process of grinding raw fly ash starts with sieving the fly ash using 325 micron mesh to avoids clumped fly ash being fed into the chamber. Then by using screw feeder, the raw fly ash is fed into the grinding chamber with feeding rate of 1,569.0 grams/hour. From grinding chamber the result of ultra fine fly ash then discharges into dust collecting bag. The process is stopped every time after grinding around 1,250 grams of raw fly ash as that is the capacity of grinding collecting system.

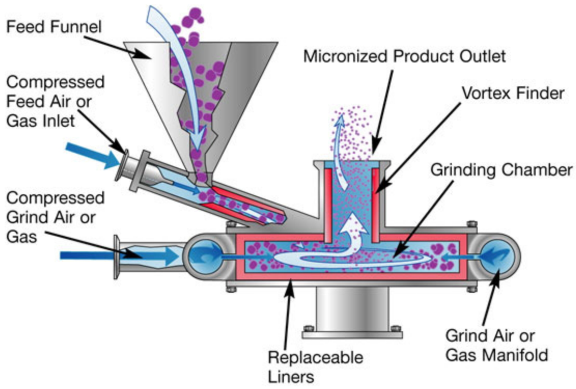


Figure 3.2: Particle to particle impact mechanism inside micronizer grinding chamber

Figure 3.3: Grinding raw fly ash in Micronizer

The increase of fineness of fly ash after the grinding was tested using Blaine air permeability test apparatus which measures the surface area of fly ash (ASTM C 204 - 00, 2000, Kett, 2000). Increase in the surface area leads to more fineness of the material. The Blaine air permeability test measures the time needed for the liquid to drop from the top mark to the bottom mark in the manometer. The drop of the liquid is caused by the air that passes through the compacted material inside the stainless steel plunger. Hence, the longer dropping time indicated that there are less voids existing in the compacted granular material which is put inside the plunger, and therefore also indicated that the material is finer.

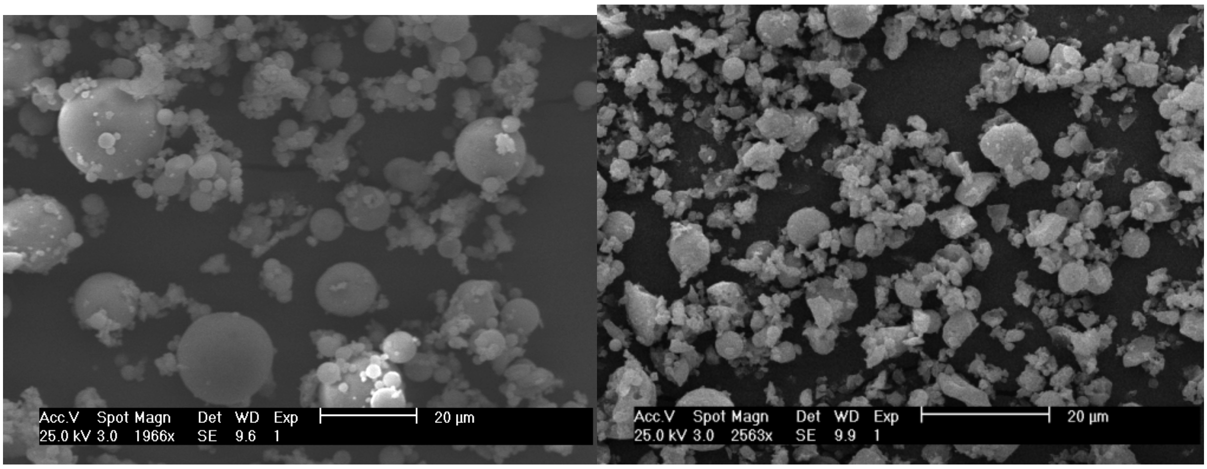
(a) (b)

Figure 3.4: (a) Blaine air permeability test apparatus and (b) detail of stainless steel plunger

The result showed that the surface area of fly ash increases from 364 m^2/ kg in raw fly ash to 525 m^2/ kg in ultra fine fly ash based on cement fineness. It indicates that the fineness of fly ash increased by 40% after the grinding process in micronizer.

Also, Philips XL30 scanning electron microscope was used to observe the picture of fly ash particle. Both pictures at **Figure 3.5** using a scale of 20 μm show the difference between the particle size of raw fly ash and the ultra fine fly ash from Scanning Electron Microscopic (SEM) analysis. It proves that the particle size of ultra fine fly ash is smaller than that of the raw fly ash. The picture also shows that the smaller particle size of ultra fine fly ash does not change the spherical shape of particle.

As a comparison to the use of ultra fine fly ash, an investigation on concrete properties using raw fly ash was also conducted. Before the raw fly ash was used it was sieved using 1.18 mm mesh to avoid clumped fly ash when it was mixed into concrete.



a) Raw fly ash (fly ash) **b) ultra fine fly ash (UFFA)**

Figure 3.5: Scanning Electron Microscopic analysis of fly ash

3.2.2. Lime water

As high silica content in fly ash needs $Ca(OH)_2$ to form C-S-H gel in cement hydration, this research used lime water [$Ca(OH)_2$], a kind of alkali liquid, as mixing water. The use of lime water to improve the alkali substance in high volume fly ash concrete is in line with geopolymer concrete production which is produced by making a reaction of alkaline liquid with silicon and the aluminium from by-product material (Davidovits, 1991, Vijai et al., 2010)

Hydrated lime after dissolving in tap water

Lime water after sedimentation for 24 hours

Figure 3.6: Lime water as mixing water

The saturated lime water was made by dissolving 3 grams of hydrated lime powder in 1 litre of tap water, as less than 2 grams of lime can dissolve into tap water (Concrete Construction Staff, 1983). After 24 hours sedimentation, the top layer of the saturated lime water was taken and used as mixing water while the solid hydrated lime was left on the bed. Moreover, the concentration of saturated lime water in molar can be determined, by assuming 2 grams of lime dissolved into 1 litre of tap water using the following formula:

$$\text{Mol of } Ca(OH)_2 = \text{gram/ Molar mass} = 2/ [40 + 2 \times (16 + 1)] = 0.03 \text{ mol}$$

$$\text{Molar of } Ca(OH)_2 = \text{mol/ litre} = 0.03 \text{ M}$$

The concentration of saturated lime water as alkali solution for mixing water is very low in comparison to alkali solution in geopolymer concrete production. In geopolymer concrete production the alkali solution might have concentration of 8M to 16M (K.A et al., 2011, Lloyd and Rangan, 2010). However, the low alkali concentration of lime water was used as additional chemical substance in the concrete since high volume fly ash concrete generally could be produced without supplementary chemical admixture.

The properties of saturated lime water were tested for its density and its pH, and the result shows that the saturated lime water has different properties compared to tap water as can be seen in **Table 3.3**.

Table 3.3: Properties of mixing water

Water	Density	pH
Tap water	0.9909	7.3
Saturated lime water	0.9917	11.4

The density of saturated lime water was slightly higher than that of tap water since some hydrated lime particles are dissolved in it (0.08%). Furthermore, with the pH of 11.4 the lime water becomes a kind of alkali liquid (Roberts, 2008). The alkalinity of lime water which resulted from dissolving of $Ca(OH)_2$ (hydrated lime) will be useful when reacting with a pozzolanic material with high silica content, such as fly ash.

3.2.3. Setting time of fly ash

Setting time test aims to find out the normal consistency and setting time of binder and it becomes a very important criterion to determine the length of the delay periods (Erdem et al., 2003).

Normal consistency is about finding out the amount of mixing water to mix with binder material to produce a standard cement paste in certain plasticity state. The normal consistency test was conducted in a vicat apparatus test by penetrating cement paste using standard plunger until the plunger achieved penetration of 5-7 mm from the base of the vicat ring in 30 seconds. The cement paste was made by mixing cement with water in a small mixer and then putting it in the vicat ring for normal consistency test. The experiment was carried out for several times to adjust the amount of mixing water needed until the normal consistency of the binder paste was achieved. Once the normal consistency of binder was achieved, the test was continued for initial setting time test of the binder.

Normal consistency test
using standard plunger

Initial setting time test
Using standard vicat needle

Figure 3.7: Vicat apparatus for setting time test

There are two characteristics of setting time, the initial set and final set. Visually, initial set of concrete is the stage when the concrete cannot be properly handled and placed into the formwork. The final set corresponds to the stage when concrete starts to be hardened (Ramachandran, 1995). This research tested initial setting time test which tested the time needed for the binder paste from the condition of fresh cement paste until the set was achieved. The initial setting time test starts by penetrating standard vicat needle (1 mm diameter) to binder paste until the needle only penetrates 25 mm from the top of cement paste.

There are 4 combinations of setting time test in this research focusing on setting time of ultra fine fly ash as binder and the use of lime water as mixing water. The combinations are:

a. Portland cement and tap water
b. High volume raw fly ash and tap water
c. High volume ultra fine fly ash and tap water
d. High volume ultra fine fly ash and lime water

The result of normal consistency and initial setting time is shown in the **Figure 3.8.** In the figure, the bottom curve shows the w/b ratio needed to produce normal consistency of binder whereas the top curve shows the initial time set for each binder.

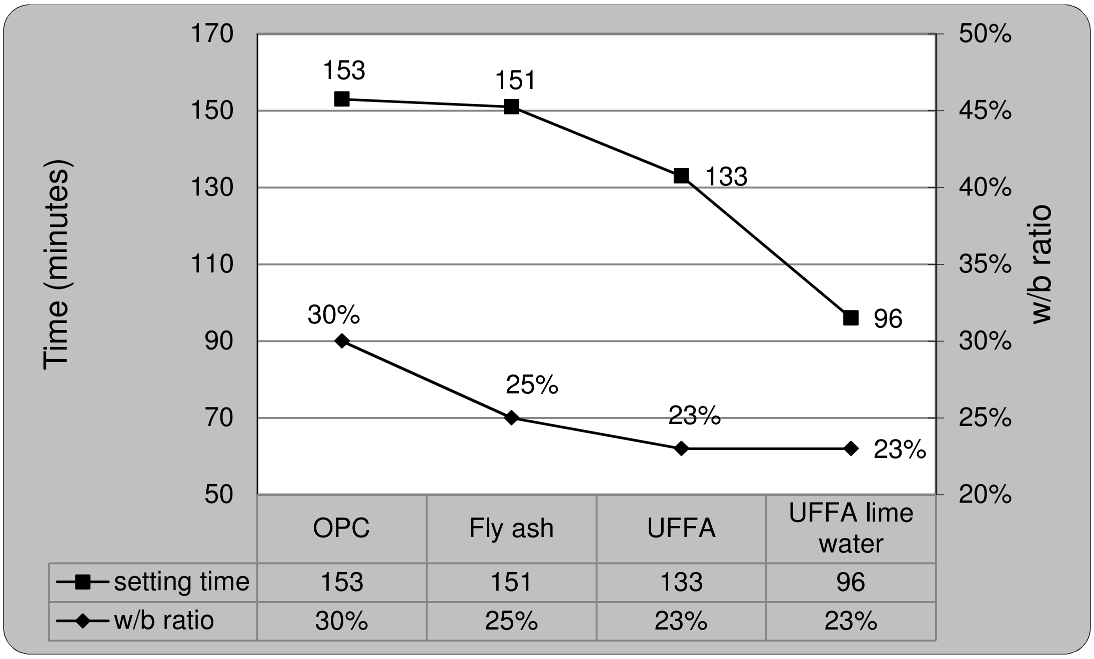


Figure 3.8: w/binder ratio for normal consistency of cement paste and initial setting time

The figure of w/binder ratio for normal consistency of cement paste and initial setting time (**Figure 3.8**) shows that less amount of water is needed for normal consistency of high volume fly ash. This is because of the spherical shapes of the fly ash that reduces the friction between cement and aggregates and results in an increase of workability of fresh concrete (Sata et al., 2007). In addition, as ultra fine fly ash has a larger amount of small spherical size particles in comparison to raw fly ash, it needs less water for normal consistency when used as cement replacement.

The initial setting time figures out the reactivity of binder demonstrates that the lesser the water is used in high volume fly ash the faster the reaction is in the binder at early ages. This is in line with what has been stated by Malhotra and Mehta (2005), i.e. the early age strength in high volume fly ash can be obtained using a water binder ratio of less than 0.4. The use of saturated lime water as mixing water increases reactivity of binder compared to the use of tap water in high volume ultra fine fly ash, as the amount of alkali solution is increased.

3.2.4. Basalt fibre

High strength concrete is beneficial in reducing the self-weight of concrete structures, however; the low ductility needs to be addressed. To improve the ductility of the high strength concrete this research used basalt fibre as a strengthening material. The basalt fibre was manufactured by Kamenny Vek Ltd. located at Dubna, Moscow, Rusia and the type of the basalt fibre is BCS 20-1", which has material properties as can be seen in **Table 3.4**.

Table 3.4: BCS 20-1" data sheet (Kamenny Vek, [no date])

BCS	Basalt continuous strand
Diameter	20 µm
Cut length	1 inch (25.4 mm)
Moisture content	< 0.03%

To understand the durability of basalt fibre, a durability test of basalt fibre under different chemical environment was conducted. The durability test was conducted by immersing 45 grams of basalt fibre in three different aggressive solutions i.e: 3% CaCl solution, 10% $NaSO_4$ solution and 1 Molar NaOH solution. The concentration of CaCl and $NaSO_4$ was based on durability test of concrete (Hooton et al., 1997, Tikalsky and Carrasquillo, 1992) whereas the concentration of NaOH was based on previous research for durability of basalt fibre (Sim et al., 2005).

The durability of basalt fibre after immersing in 3 different solutions was tested for the weight change of basalt fibre after immersing for 3 days,7 days, 21 days, 28 days, 35 days, 49 days, 56 days, 70 days and 91 days.

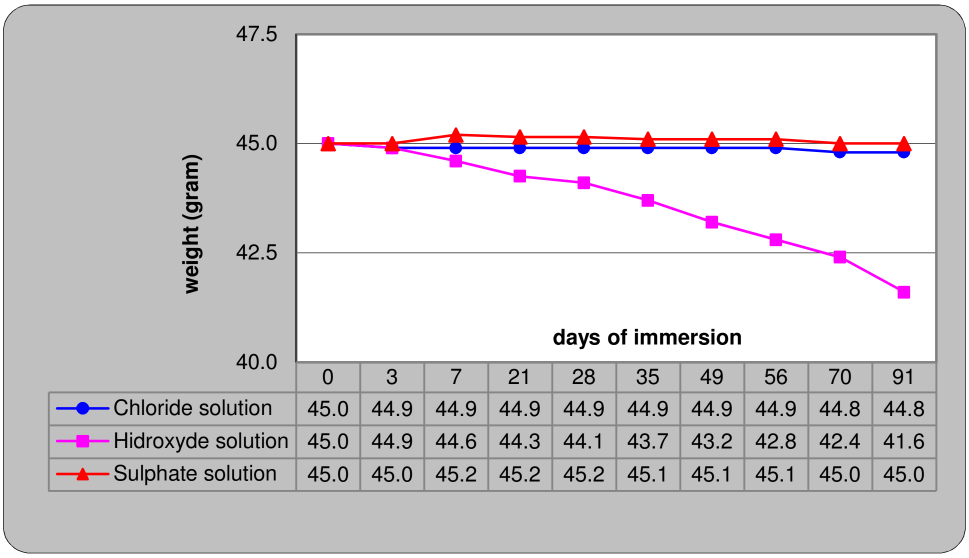


Figure 3.9: Weight change of basalt fibre in three different solutions

The result of the test in **Figure 3.9**, weight change of basalt fibre in three different solutions shows that the basalt fibre is not suitable to be used as material in alkali environment. The weight of basalt fibre decreases continuously for longer time of immersion and there is an indication that some of the basalt fibre dissolve into the solution. The picture of test (**Figure 3.10**) also confirms that the basalt fibre in alkali solution disperses which is different from the condition of basalt fibre in the chloride solution and in the sulfate solution.

The decreasing weight of basalt fibre in alkali solution is in line with the result from former research which showed that basalt fibre lost their volume more promptly in aggressive alkali solution (Sim et al., 2005).

CaCl solution | $NaSO_4$ solution | NaOH solution

Figure 3.10: Basalt fibre shape after immersing in three different solutions

3.2.5. Mix design of high strength concrete

This research uses the mix design for high strength concrete which was prepared based on proposed method by Aitcin for high performance concrete mix design (Aïtcin, 2004). This method was an elaboration of the earlier method which enables the possibility for some development and adjustment from Mehta/Aitcin mix design method, one of the easier methods in preparing mix design of high strength concrete (Alves et al., 2004).

The mix design of high strength concrete based on proposed method by Aitcin for high performance concrete mix design is based on the following five principles i.e.

a) The w/binder ratio used is appropriate with the design compressive strength of concrete based on the monogram (**Figure 3.11**). The design compressive strength of concrete was tested on 100 mm diameter and 200 mm height cylinders at curing age of 28 days.

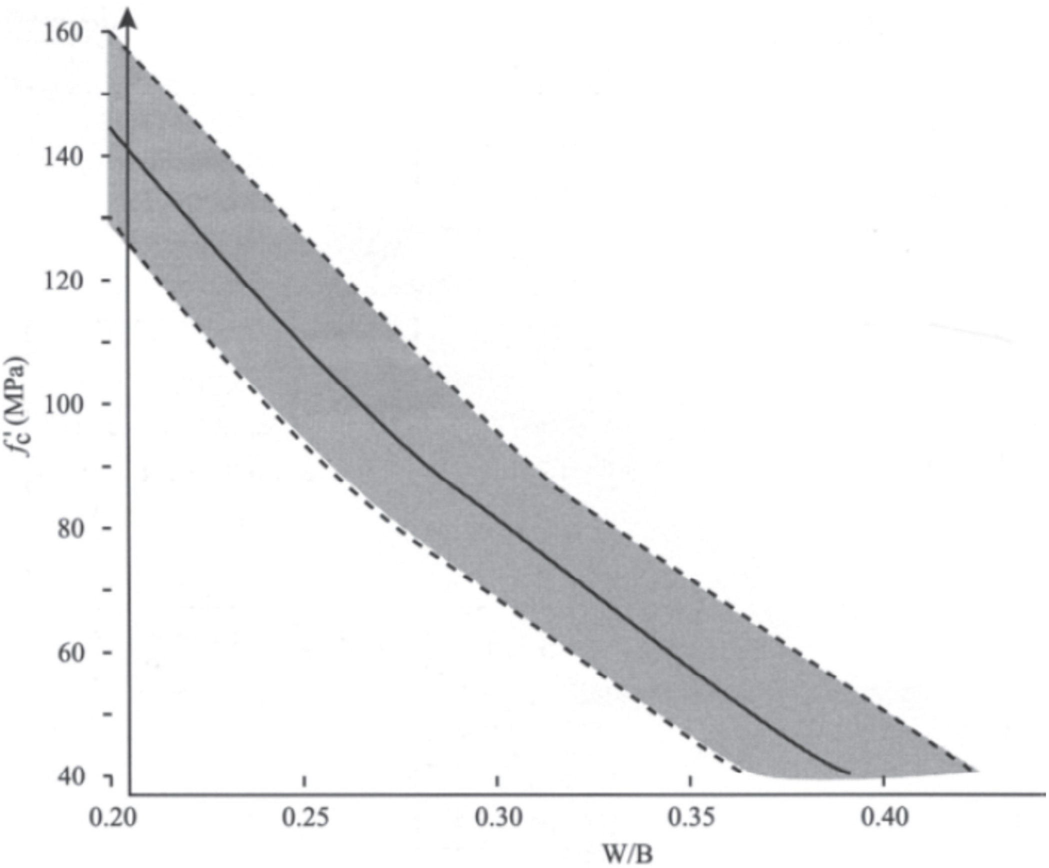


Figure 3.11: Proposed w/b ratio vs compressive strength relationship (Aïtcin, 2004).

b) The amount of water used is determined to achieve 200 mm of slump after 1 hour of batching. To simplify this step, a recommendation of water content is given based on the concept of saturation point of superplasticizer. Also, when the saturation point is not known, the water content of 145 litre can be used at the beginning (**Figure 3.12**).

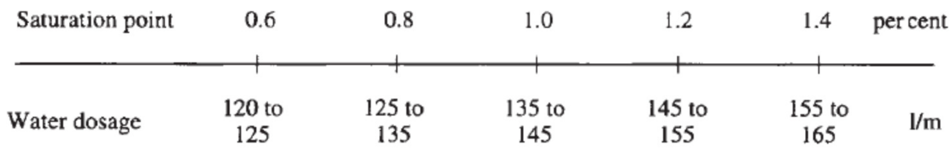


Figure 3.12: Determination of the minimum water dosage (Aïtcin, 2004)

c) The dosage of superplasticizer can start from 1%.

d) The coarse aggregate content based on its typical particle shape can be found from the chart provided in **Figure 3.13**. A content of 1,000 kg can be used for a start when there is a doubt about the coarse aggregate shape or the shape of coarse aggregate is not known.

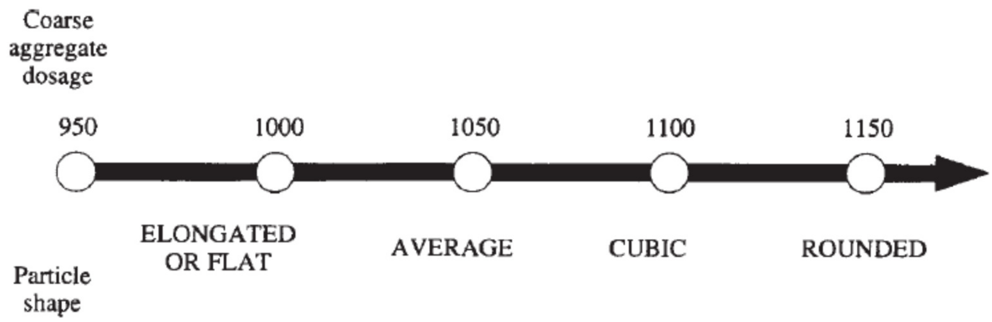


Figure 3.13: Coarse aggregate content (Aïtcin, 2004)

e) Air content of high performance concrete can vary from 1% to 3% depending on the mix proportion. Therefore, a value of 1.5% of air content can be used to start with.

In addition, the mix proportion of high strength concrete using proposed method by Aitcin can be prepared using the single sheet provided.

BATCH I.D.:

MIX DESIGN SHEET

Comp. Strength:	MPa

Table A	G_c	%
Cement	3.14	

Aggregate	G_{SSD}	%		
		w_{abs}	w_{tot}	w_h
Coarse				
Fine				

$w_h = w_{tot} - w_{abs}$ $\qquad$ $M = M_{SSD}\,(1 + w_h)$

SUPERPLASTICIZER		$M_{sol} = C \times \frac{d}{100}$	$V_{liq} = \frac{M_{sol}}{s \times G_{sup}} \times 100$	$V_w = V_{liq} \times G_{sup} \times \left(\frac{100-s}{100}\right)$	$V_{sol} = V_{liq} - V_w = V_{liq}\left[1 - \left(\frac{100-s}{100}\right) \times G_{sup}\right]$
Spec. gravity (G_{sup})	Solids dosage s (%)	15 E	24 F	21 G	11 H

	1		2	3	4	5	6
MATERIALS	Content kg/m³		Volume l/m³	Dosage SSD conditions kg/m³	Water correction l/m³	Composition 1 m³	Composition Trial batch
WATER	2		2	2		23	25
$\frac{W}{B} = 0.$ 1							
CEMENT	3	4-1	8-1	4-1		4-1	26-1
		4-2	8-2	4-2		4-2	26-2
		4-3	8-3	4-3		4-3	26-3
COARSE AGGREGATE	5		9	5	18	17	27
FINE AGGREGATE			13	14	20	19	28
AIR	PERCENT 6 %		10	0			
SUPER-PLASTICIZER	7 %		11	15	21 -	24 V_{liq}	29 V_{liq}
TOTAL			12	16	22		30

Figure 3.14: Mix design sheet for high strength concrete (Aïtcin, 2004)

3.2.6. Concrete specimens

This research observed 3 factors to produce high strength concrete, i.e. the use of high volume ultra fine fly ash, the use of basalt fibre as strengthening materials and the use of lime water to increase alkali substance in high volume ultra fine fly ash concrete. This research commenced by finding the optimum concrete mix design of high strength concrete using high volume ultra fine fly ash. The optimum concrete mix design was obtained with testing a series of mortars for compressive strength with different mix designs. From the strength results of high volume fly ash mortar, a mix proportion was chosen to prepare mix proportions of high volume ultra fine fly ash concrete. The high volume ultra fine fly ash concrete was tested for its mechanical properties consisting of the fresh concrete test, mechanical properties of the hardened concrete and the durability of the high strength concrete.

The mortar specimens have dimensions of 50 x 50 x 50 mm cubes for compressive strength test and prisms of 160 x 40 x 40 mm for flexural strength test. In addition, water absorption test was also conducted using mortar prisms. The dimension of concrete specimens comprises of cylinder of ϕ 100 mm x 200 mm height for compressive strength test, water absorption test and durability test of concrete. In addition, concrete specimens for flexural strength test has dimension of 350 x 100 x 100 mm.

To compare the result of high volume ultra fine fly ash concrete using lime water as mixing water and basalt fibre as strengthening material, a series of control concrete mixes was also investigated. Therefore, all variations of mix proportion used in this experiment are:

a) High volume UFFA concrete without basalt fibre, using tap water as mixing water.
b) High volume UFFA concrete with basalt fibre, lime water as mixing water.
c) High volume raw Fly Ash concrete with basalt fibre, tap water as mixing water.
d) High volume raw Fly Ash concrete without basalt fibre, lime water as mixing water.
e) OPC concrete without fibre, tap water as mixing water.
f) OPC concrete with fibre, tap water as mixing water.
g) OPC concrete with steel fibre, tap water as mixing water.

The number of specimens needed for this experiment is shown in **Table 3.5**, matrix of specimens. For mortar tests 148 mortar cubes and 100 mortar prisms were used. Also, concrete test needed 273 concrete cylinders and 84 concrete prisms.

Table 3.5: Matrix of specimens

	Dimension of specimen	Testing age				
A. Mortar test			**Number of specimens**			
Experimental design					There are 4 variations of mix proportion	
Compressive strength test	cubes 50 x 50 x 50 mm	28 and 56 days	2 x 5 x 4 =	40	No. 1 :	Mortar using w/b = 0.30 and UFFA content 20%
					No. 2 :	Mortar using w/b = 0.30 and UFFA content 50%
					No. 3 :	Mortar using w/b = 0.35 and UFFA content 20%
					No. 4 :	Mortar using w/b = 0.35 and UFFA content 50%
Strength development					There are 4 variations of mix proportion	
Compressive strength test	Cubes 50 x 50 x 50 mm	7, 14, 21, 28 and 56 days	5 x 5 x 4 =	100	No. 1 :	OPC mortar
Flexural strength test	Prism 160 by 40 by 40 mm	7, 14, 21, 28 and 56 days	5 x 5 x 4 =	100	No. 2 :	High volume UFFA mortar
Water absorption	Prism 160 by 40 by 40 mm	56 days	1 x 2 x 4 =	8	No. 3 :	High volume raw fly ash mortar
					No. 4 :	High volume UFFA mortar using lime water
B. Concrete test					There are 7 variations of concrete mix proportion	
Compressive strength	Cylinder dia. 100 x 200 mm	28, 56, 84, 180 days	4 x 3 x 7 =	84	No. 1 :	High volume UFFA without basalt fiber, tap water
Modulus of elasticity	Cylinder dia. 100 x 200 mm	56 days	1 x 3 x 7 =	21	No. 2 :	High volume UFFA with basalt fiber, lime water
Modulus of rupture	Prism 350 by 100 by 100 mm	28, 56, 84, 180 days	4 x 3 x 7 =	84	No. 3 :	High volume Raw Fly Ash with basalt fibre, tap water
Water absorption	Cylinder dia. 100 x 60 mm	28, 56, 84, 180 days	4 x 3 x 7 =	84	No. 4 :	High volume Raw Fly Ash without basalt fibre, lime wate
Rapid chloride penetration (RCPT)	Cylinder dia. 100 x 50 mm	56 and 180 days	2 x 3 x 7 =	42	No. 5 :	OPC without fibre, tap water
Sulfate attack	Cylinder dia. 100 x 60 mm	180 days	1 x 3 x 7 =	21	No. 6 :	OPC with fibre, tap water
Carbonation test	Cylinder dia. 100 x 60 mm	180 days	1 x 3 x 7 =	21	No. 7 :	OPC with steel fibre, tap water

4 x 3 x7

Number of variation in mix proportion
Number of specimen in each test
Number of testing age

UFFA = Ultra fine fly ash

3.3. Test method

3.3.1. Design of experiment

Design of experiment or experimental design is about planning and conducting experiments and about analysing the resulting data, so that valid and objective conclusions are obtained (Montgomery, 2009). If experiment is a representation of a model as can be seen in **Figure 3.15**, planning an experiment is about preparing a process as a combination of operations, machines, methods, people and other resources in which some of variables are controllable and other variables are uncontrollable, and transforming some input into an output that has one or more response observable variables.

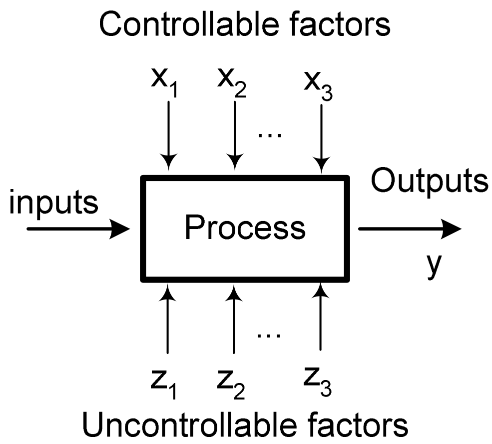


Figure 3.15: General model of a process (Montgomery, 2009)

The experimental design utilizes multivariate optimization, a technique that is being used increasingly in chemistry, chemical engineering, food engineering, pharmacology and others fields. The major advantage of multivariate design is that it has a higher applicability, minimal costs and a high degree of accuracy. In addition, interaction among factors can only be discovered by using multivariate strategies (Vieira et al., 2010). Moreover, the objective of the experimental design may include:

a) Determining which variables are most influential on the response.
b) Determining where to set the influential controllable variables so the output is almost always near the desired nominal value.
c) Determining where to set the influential controllable variables to lead the small variability in output, and
d) Determining where to set the influential controllable variables to minimize the effect of uncontrollable factors.

In design of experiment the process of preparing input and analysing output data as described in Minitab tutorial follows the following stages:

a) Name factors and set factor levels of design experiment.
b) Randomize the factor and store the design experiment.
c) Collect and enter data of experiment based on randomized factor.
d) Identify important effect
e) Draw conclusion

Factor is a set of treatment for the research object which has a common feature, and therefore the response of those factors can be evaluated. When starting design experiment, it is very important to recognize the problem to select the considering factor in experiment and response variable to be analysed. The factor in experiment can be classified as potential design factor and nuisance factor; however, the potential design factor is the main factor that can be analysed as it gives the variation of result.

Each design factor consists of a level which figures out the different treatment of each factor. In addition, when the design of experiment has two levels for each factor, the result is considered as linear response.

With the factors and level being used in design of experiment, a randomization is conducted and resulted in:

a) Order of running experiment

b) Combination of each factor and level in experiment.

When not all of the experiments can be afforded; the design experiment can be carried out in a half fraction by neglecting higher order interaction between factor and levels. For example, if there are three observed factors which have two levels for each factor, all of possible combination for experiment become $2^3 = 8$ as can be seen in **Table 3.6.**

Table 3.6: All possible combination of 2^3 factorial design (Montgomery, 2009)

Treatment combination	I	A	B	C	AB	AC	BC	ABC
a	+	+	-	-	-	-	+	+
b	+	-	+	-	-	+	-	+
c	+	-	-	+	+	-	-	+
abc	+	+	+	+	+	+	+	+
ab	+	+	+	-	+	-	-	-
ac	+	+	-	+	-	+	-	-
bc	+	-	+	+	-	-	+	-
(1)	+	-	-	-	+	+	+	-

Note: + High level
- low level

However, the use of half fraction for design of experiment leads to two possible combinations that can be run in experiment as can be seen in **Figure 3.16**, and therefore; we can choose between these two available options in conducting the experiment.

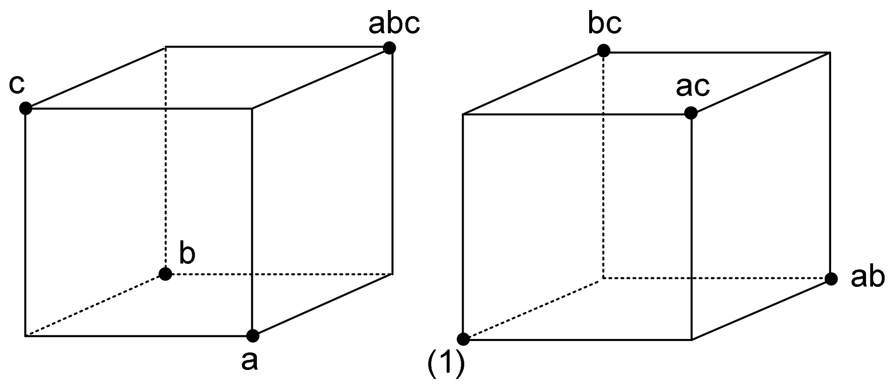


Figure 3.16: The two one half fractions of the 2^3 design

After randomizing the factors, the next step in design of experiment is collecting data by conducting experiment based on treatment combination. The result of the experiment associated with the treatment combination can be used in data analysis to find out the response of each factor to the result, the important factor in experiment and to draw a conclusion. Software called MINITAB R 15 was used for design of experiment, from preparing the mix proportion combination to analyse the result.

3.3.2. Strength of mortar

The strength of mortar test was conducted when studying the design of experiment of ultra fine fly ash mortar and the strength development of high volume ultra fine fly ash mortar. The design of experiment was conducted to study the influence of ultra fine fly ash content and water/ binder ratio on compressive strength of mortar. Moreover, the strength development of high volume ultra fine fly ash mortar will be used as a guide for mix proportion preparation for high volume fly ash concrete.

The strength of the mortar was tested for its compressive strength and its flexural strength. The compressive strength of mortar was tested using 50 x 50 x

50 mm mortar cubes whereas flexural strength of mortar was tested using 160 x 40 x 40 mm mortar prisms.

3.3.3. Strength of concrete

In the experimental program, three basic tests for mechanical properties of concrete were conducted i.e. tests for compressive strength, modulus of rupture and modulus of elasticity. The compressive strength of concrete and the modulus of rupture were tested at the ages of 28 days, 56 days, 84 days and 180 days. The compressive strength was tested on concrete cylinders ϕ 100 mm and 200 mm height after water curing for 56 days. The modulus of rupture was tested using concrete prisms with dimension of 100 x 100 x 350 mm after curing in the water for 56 days. Besides those strength tests of the concrete, the test for modulus of elasticity was also conducted at the specimen's age of 56 days.

In addition to the strength properties of concrete, the durability properties of concrete were assessed using water absorption test, sulfate resistance test, carbonation test and rapid chloride penetration test.

3.3.4. Water absorption

Water absorption test was conducted based on Australian Standard (AS 1012.21., 1999) to find out the immersed absorption, the saturated absorption and the apparent volume of permeable voids (AVPV). Immersed absorption is the percentage water content by mass of initially dry concrete specimens which have been soaked in water for 48 h. In addition, saturated absorption is the ratio of the mass of water that can be held in saturated concrete to the oven-dry mass of concrete specimen. Furthermore, apparent volume of permeable voids (AVPV) expressed as a percentage describes the apparent volume of interconnected voids space of a concrete specimen which is emptied during the specified oven drying and filled with water during the subsequent immersion and saturation.

The saturated absorption was used instead of boiling absorption as sta ted in standard (AS 1012.21., 1999) considering that the saturated absorption gave a higher water absorption and porosity result in comparison to boiling absorption (Wilson et al., 1999). The saturation of concrete specimen followed the procedure to saturate concrete specimen before being tested in rapid chloride ion penetration standard test (ASTM C 1202 -97., 2002).

The immersion absorption test follows these procedures:

a) Weighing the specimen to the nearest 0.1 grams and drying in an oven in a dish at a temperature of 100℃ to 110℃ for maximum of 24 hours. After removing each specimen from the oven, allowing it to cool then determining the oven-dry mass of the cooled specimen, and recording as M_1 to the nearest 0.1 grams.
b) After final drying, cooling and weighing, immersing the specimen in water for not less than 48 hours.
c) Surface-drying the saturated specimen by removing the surface moisture with a towel and determining its mass M_{2i} to the nearest 0.1 grams.

The procedure for saturated absorption test and apparent volume of permeable voids test uses the following steps:

a) Preparation of specimen.

   Placing specimen in vacuum desiccator then sealing desiccator and starting vacuum pump. Pressure should decrease to less than 1 mmHg (133 Pa) within a few minutes, then maintaining vacuum for 3 hours. Filling separatory funnel or other container with the de-aerated water prepared previously. With vacuum pump still running, opening water stopcock and draining sufficient water into beaker to cover specimen. Closing water stopcock and allowing vacuum pump to run for one additional hour, and continuing to soak specimen under water for 18 ± 2 hours.

b) Surface-drying the saturated specimen and determining its mass M_{3s} to the nearest 0.1 g.

c) Suspending the specimen, after immersion and saturating, by a rack or other support and determine the mass M_{4s} of the specimen in water to the nearest 0.1 g.

The water absorption properties can be calculated using following equation (AS 1012.21., 1999):

For specimens tested for immersed absorption (*Ai*)

$$Ai = \frac{(M_{2i} - M_1)}{M_1} x100\%$$

For specimens tested for saturated absorption (*As*)

$$As = \frac{(M_{3s} - M_1)}{M_1} x100\%$$

For specimens tested for apparent volume of permeable voids (AVPV)

$$AVPV = \frac{(M_{3s} - M_1)}{(M_{3s} - M_{4s})} x100\%$$

Where:

M_{2i} : mass of surface-dry specimen after immersion

M_1 : oven-dry mass of the cooled specimen

M_{3s} : mass of surface-dry saturated specimen

M_{4s} : mass of surface-dry saturated specimen in water

3.3.5. Sulfate resistance test

The current procedure of sulfate test is described in standard test of potential expansion of mortars exposed to sulfate (ASTM C 452 – 02, 2002) and standard test for length change of mortars exposed to a sulfate solution (ASTM C 1012 – 02, 2002). However, there are some criticisms from some researchers regarding the test method as summarised by Kurtis et al., (2001) i.e.

a) ASTM C452 does not represent field conditions because inadequate curing of cement results in anhydrous cement compounds being exposed to attack; softening-spalling attack is ignored by ASTM C452 and ASTM C1012.
b) Standard specifications for sulfate-resisting cements (ASTM C452 and C1012) generally ignore the acid-type sulfate attack, which is more typical in the field.
c) Cement composition affects the rate of consumption of sulfate ion and introduces variability in ASTM C1012; pH during testing is 3–5 orders of magnitude different from field conditions; C1012 tests are protracted because of decreasing amount of sulfate ion in solution.
d) Cause of expansion not determined by the tests; do not address formation of ettringite during storage and expansion.
e) Addition of sulfate in ASTM C452 is not representative of field conditions; both tests are too sensitive to specimen size and geometry.

Therefore, an improvement in existing sulfate test method as given in accelerated test to predict the service life of building component materials (ASTM E 632-82, 1996) was proposed (Ferraris et al., 2006). The improvement is in regard to some phenomena which influence the interaction of sulfate and concrete, i.e:

a) Concrete properties: absorption and diffusion of sulfate or resistance to the ingress of sulfate solutions.
b) Cement paste properties: chemical reaction between the hydration product and the sulfate ions.
c) Influence of environmental conditions (type of immersion and temperature) or referred as physical attack.

There are four proposed test methods developed to address the those three phenomena above i.e. absorption of water by a concrete specimen (accepted as ASTM standard), diffusion of sulfate in saturated specimens, a specimen test to determine the cement's resistance to sulfate attack, and a test to determine the resistance to sulfate attack when a concrete is not totally immersed in the solution.

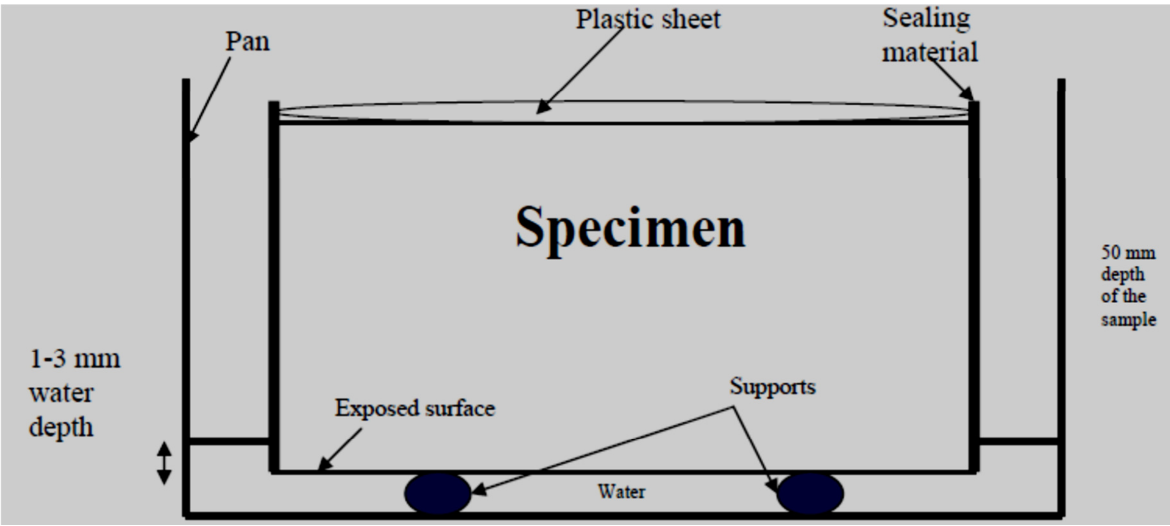


Figure 3.17: Schematic of sulfate absorption test (Byrami, 2006)

As the proposed method was accepted as ASTM standard only for water absorption, the procedure of sulfate test in this research followed the standard (ASTM C 1585, 2004). The sulfate sorption test is focusing on the investigation of sulfate attack using absorption mechanism for preconditioning specimens. The preconditioning of concrete specimens aims to achieve the saturation of 60%, and this saturation is paramount as the dry specimens will lead to high absorption whereas saturated specimens will make no absorption. The preparation and the testing of specimen to get saturation of 60% follow the procedures as described in ASTM C1585 standard, i.e.

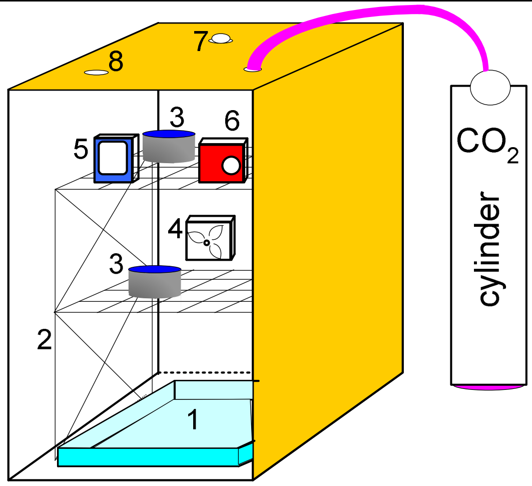
a) Place the test specimens in humidity chamber with humidity of 80 ± 3% and temperature of 50 ± 2^{o}C for 3 days.
b) After 3 days, place the specimens inside sealed container for minimum of 15 days in a room with temperature of 23 ± 2^{o}C. After storing the specimens for 15 days, the test can be started.
c) Remove the specimens from the container and record the weight. Also measure the diameter of specimens at the surface which will be exposed to sulfate solutions.
d) Put epoxy on curved specimens to seal the specimens. Also, put a loosely attached plastic sheet on the surface which will not be exposed to sulfate solutions.
e) Record initial weight of specimens then put the specimens in sulfate solution. Record the weight of specimen at 60 seconds, at 5 minutes, at 10 minutes, at 20 minutes, at 30 minutes, at 60 minutes, and then continue recording of the weight every hour up to 6 hours.
f) After the initial weight record, take measurement of the weight everyday up to 8 days. Put the record in a table and graph to get the initial absorption and secondary absorption.

3.3.6. Carbonation test

Carbonation test of concrete was conducted based on RILEM recommendation on measurement of concrete carbonation depth. It measures the depth of alkali substance inside the concrete which is mainly $Ca(OH)_2$, being reacted with CO_2 gas. The depth of carbonation can be indicated using phenolphthalin liquid which is sprayed to the concrete after exposure to carbon gas environment (NT Build 357, 1989, RILEM CPC-18, 1984).

The phenolphthalein liquid was made by dissolving 1% phenolphthalein powder into 70% ethanol liquid. The phenolphthalein liquid will change the colour of un-carbonated concrete into purple and remain colourless for carbonated concrete. Hence, the depth of carbonation can be determined.

The carbonation test for this research was accelerated carbonation test which employed a carbonation chamber to keep the specimen for testing at 7 days and 28 days. The carbonation chamber was maintained to have carbon concentration of 3.5% and relative humidity of 65%. Besides, the temperature should be maintained at 25°C (Jones et al., 2000).



Note:

1. Calcium nitrite solution
2. Selves
3. Specimens
4. Fan
5. Humidity and temperature sensor
6. Oxygen sensor
7. Release valve
8. Cable inlet, to give power and monitor the sensor

Figure 3.18: Schematic of carbonation chamber

The preparation and testing of specimen was conducted following these procedures:

a) Cut the specimen from concrete cylinder of ϕ 100 x 200 mm height into small concrete cylinder of ϕ 100 x 60 mm height
b) Put epoxy on the flat surface, leave the curved surface for exposure in carbon gas
c) Place the specimens inside the carbonation chamber and control the humidity using calcium nitrite to get constant humidity of 65% (Creahan, 1991, Rockland, 1960).
d) Open the valve so that the CO_2 gas will get inside the chamber and monitor the concentration of CO_2, adjust the concentration of CO_2 inside the chamber by opening and closing the CO_2 valve. Run the fan to make even concentration of CO_2 inside the chamber.
e) Stop the test on the day of observation and then cut off the specimen longitudinally. Spray the cut off specimen using phenolphthalein solution to check the depth of carbonation.

3.3.7. Rapid chloride penetration test

There are three mechanisms of chloride ion penetrating into concrete, i.e. capillary absorption, hydrostatic pressure, and diffusion (Stanish et al., 1997). Capillary absorption of ion concrete occurs if concrete is exposed to wet and dry condition. When water which possibly contains chloride ions meets dry surface of concrete, it will be absorbed by pore structure in concrete so that concrete ion will ingress into the concrete. The next mechanism of chloride ion penetration into the concrete is hydrostatic pressure or permeation which employs different hydrostatic pressure gradient. The concrete surface having higher pressure makes the chloride ion drive into concrete.

The last mechanism of chloride ion penetrating into concrete is diffusion which enables chloride ion to ingress into concrete and can bring chloride ion into rebar. This mechanism happens if the concrete has continuous liquid phase and there is chloride gradient in it. Therefore, this research will investigate the chloride penetration into concrete using diffusion mechanism as describe in standard (ASTM C 1202 -97., 2002) which was developed firstly by Whiting Davis in 1981 for Federal Highway Administration, Offices of Research & Development, Materials Division (CCAA Report, 2009).

This rapid chloride penetration of concrete is tested on small cylinder of ϕ100 x 50 mm height in electrical testing apparatus where one surface of the cylinder is exposed to 3% NaCl solutions and the other surface is exposed to 0.3N NaOH solutions. To ensure that the chloride ion had only one direction penetration, the curved surface of cylinder is coated prior to the test. Also, to accelerate the penetration of chloride ion into the concrete, a constant current of 60 V DC is applied on both ends of specimens.

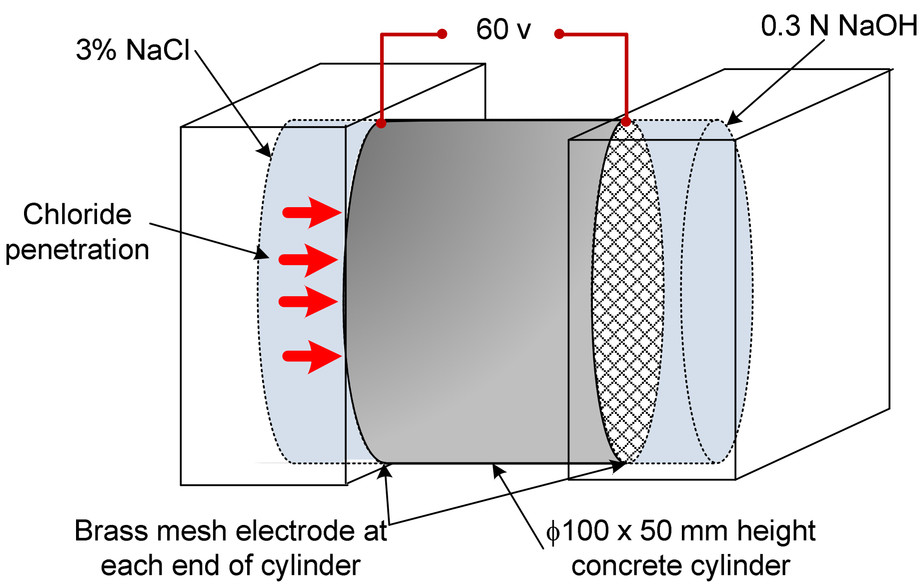


Figure 3.19: Rapid chloride penetration test

The resistance to chloride ion penetration is indicated by the current which can pass across specimens and is recorded every 30 minutes during 6-hours test (ACI Concrete Knowledge Center, 2006). The correlation between current passing across the specimens (charge passed) and chloride ion penetrability are shown in the **Table 3.7**.

Table 3.7: Chloride ion penetrability based on charge passed (ASTM C 1202 - 97., 2002)

Charge passed (coulombs)	Chloride ion penetrability
> 4,000	High
2,000 – 4,000	Moderate
1,000 – 2,000	Low
100 – 1,000	Very low
< 100	negligible

Before commencing the test, the specimen was prepared by:

a) Cutting the specimen from big concrete cylinder of ϕ 100 x 200 mm height into small concrete cylinder of ϕ 100 x 50 mm height
b) Coating epoxy around the curved surface until the epoxy is dry.
c) Saturating the specimen, using following method: vacuum the specimen for 3 hours then immediately soak into water for 18 hours.
d) The specimen is ready to be tested.

3.4. Summary of chapter 3

Chapter 3 discussed the materials and methods used in this research which can be summarised as follow:

3.4.1. Materials

1) The source of fly ash for this research came from Tarong power plant and it was classified as class F fly ash

2) Ultra fine fly ash for this research was produced by grinding raw fly ash using a micronizer, which deploys particle to particle impact mechanism using compressed air.
3) Lime water was used to increase alkali solution in concrete to produce better reactivity of ultra fine fly ash.
4) Setting time results showed that high volume fly ash paste needed less water to produce same normal consistency as OPC paste and further decrease of water was related to the use of ultra fine fly ash.
5) There are 3 factors needed to be considered to produce high strength high performance concrete, i.e. type of fly ash, kind of mixing water and the utilization of basalt fibre as strengthening material.

3.4.2. Methods

1) Design of experiment -a statistical method- was used to prepare the mix proportion combination and to analyse the strength result of concrete
2) This research was started by investigating mortar strength as the basis to prepare concrete test.
3) Mortar specimens were tested for compressive strength and flexural strength. In addition, water absorption of mortars was also investigated.
4) Strength of the concrete was studied to find out the compressive strength, the modulus of rupture and the modulus of elasticity.
5) Besides the strength of the concrete, durability test was also conducted which consisted of water absorption test, carbonation test, sulfate absorption test and rapid chloride penetration test.
6) There were eight different mortars mix proportion and eight different concrete mix proportions which were analysed during this research program.

4. Mechanical properties of high volume ultra fine fly ash mortar

Prior to testing of concrete mix proportions, it was decided to conduct an experimental study on mortar specimens using ultra fine fly ash. This study on mechanical properties of high volume ultra fine fly ash mortar is significant as it would become the basis before preparing mix proportions of concrete. In addition, tests on mix proportions of high volume ultra fine fly ash mortar prior to formulating concrete mixes is beneficial for material efficiency as mortar needs small amount of material in comparison to material needed for concrete. Mortar also merely uses fine aggregate without coarse aggregate as total aggregate. Moreover, the experiments will be constructive in drawing conclusion on the possibility of using high volume ultra fine fly ash as cement replacement to produce high strength concrete.

The study on mechanical properties of high volume ultra fine fly ash mortar comprises of two experiments. The first experiment investigated the influence of w/binder ratio and ultra fine fly ash content on compressive strength of mortar and the second experiment investigated strength development of high volume ultra fine fly ash mortar.

The first investigation of the influence of w/binder ratio and ultra fine fly ash content on compressive strength of mortar was undertaken using the theory of design of experiment, a statistical method to plan, conduct, and analyse the result of an experimental study. Besides, the second experiment on strength development of mortar was conducted to investigate the compressive strength and flexural strength development of mortar at the age of 7 days, 14 days, 21 days, 28 days and 56 days. Additionally, an investigation on mortar water absorption was also studied.

4.1. Effect of water binder ratio and ultra fine fly ash content on compressive strength of mortar

The ultra fine fly ash content and w/binder ratio are considered as major variables in the mortar mix proportion. The use of small amount fly ash as supplementary cementing material will increase the compressive strength, however; the addition of optimum amount of fly ash will decrease the compressive strength (Oner et al., 2005). Besides, the use of w/binder ratio of less than 0.4 becomes the requirement for producing high performance concrete (Aïtcin, 2004).

Therefore, an investigation was conducted on the effect of ultra fine fly ash content and w/binder ratio on compressive strength of mortar. The ultra fine fly ash was produced by grinding fly ash using a micronizer. Moreover, the term of w/binder ratio (w/b) was preferred to w/cement ratio (w/c) as the binder in the mortar consists of not only cement but also fly ash.

The former research shows the optimum amount of ultra fine fly ash which leads to the increase of compressive strength in comparison to OPC concrete was 20% (Alvarez et al., 1988). It is further argued in previous study that the use of w/cement ratio of 0.3 with the consequence of the decreasing workability is possible to produce the highest compressive strength result of concrete in comparison to higher w/cement ratio (Yasar et al., 2004) .

Hence, based on those arguments, there are two important factors to be analysed in mortar compressive strength i.e. ultra fine fly ash content as cement replacement and w/binder ratio. Each factor has two level of values to be considered. The two levels of ultra fine fly ash content as cement replacement are ultra fine fly ash content of 20% and ultra fine fly ash content of 50%. The low level of 20% was used to consider the amount of fly ash to produce optimum compressive strength of fly ash mortar whereas the high level of 50% was used to study the potentials of producing high strength mortar using high volume ultra fine fly ash.

The second factor, w/binder ratio, also comprises of two levels i.e. w/binder ratio at low level of 0.3 and w/binder ratio at high level high level of 0.35. The use of high level of w/b ratio was based on the suggestion from previous research that the w/c ratio of 0.35 is enabled to produce high strength concrete (Behnood and Ziari, 2008), Moreover, the use of low level of w/b ratio was to achieve higher strength in high volume ultra fine fly ash mortar. The two factors and their levels in design of experiment are shown in **Table 4.1**.

Table 4.1: The 2 levels of factors in the design of experiment of mortar

factors	Levels	
	Low	High
w/binder ratio	0.3	0.35
fly ash content	20%	50%

Considering those two factors with two levels needed to be studied, design of experiment was used to prepare mix proportions and analyse the result of compressive strength.

4.1.1. Design of experiment on mortar compressive strength

The design of experiment or experimental design is a statistical method to prepare and analyse the resulting data of experimental work to obtain valid and objective conclusion (Montgomery, 2009). In this research, the design of experiment was used to analyse the effect of water/ binder ratio and ultra fine fly ash content on compressive strength of high volume ultra fine fly ash mortar. Moreover, to maintain the accurate result, MINITAB software was used to perform design of experiment.

To prepare the mix proportion of high volume ultra fine fly ash mortar, the observed factors with their levels need to be randomly distributed in all experiment combinations. In addition, the order of experiment also need to be randomly performed. The randomization is common and very important in experimental design to reduce the systematic bias that influences the experiment (Antony, 2003).

The randomization of those factors and levels employed full factorial design in which all possible combination of mix proportion was tested. The design of experiment which has two levels for each observed factor is named as 2^k design. For two factors with two levels in this experiment, the number of all possible combinations is $2^k = 2^2 = 4$.

The randomization of those factors was conducted using Minitab software under design of experiment full factorial design section. The result of randomization of two observed factors of w/binder ratio and ultra fine fly ash content each of which consists of two levels by using MINITAB software is shown in **Figure 4.1, Figure 4.2** and **Table 4.2.**

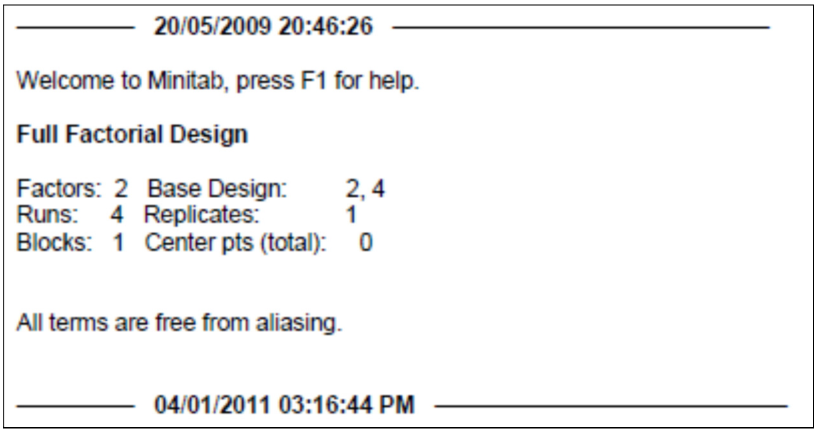
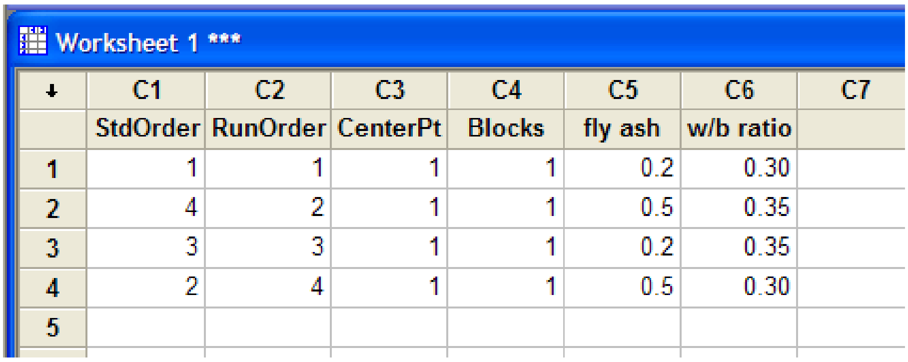


Figure 4.1: Full factorial design in Minitab session analysis



↓	C1	C2	C3	C4	C5	C6	C7
	StdOrder	RunOrder	CenterPt	Blocks	fly ash	w/b ratio	
1	1	1	1	1	0.2	0.30	
2	4	2	1	1	0.5	0.35	
3	3	3	1	1	0.2	0.35	
4	2	4	1	1	0.5	0.30	
5							

Figure 4.2: Worksheet result for randomization of two factors

Table 4.2: Full factorial design of the 2 factors in mortar's experimental design

Mix proportion number	w/binder ratio	fly ash content
1	0.30	20%
2	0.35	50%
3	0.35	20%
4	0.30	50%

In Minitab sessions the input for replicates of each experiment was 1. Although the design data for each mix proportion was 5, those specimens were mixed in one time in a mixer. Therefore, the number of replicates for each mix proportion is 1. In addition, when performing the experiment, the order of running experiment as can be seen in Minitab worksheet should follow run order

(**RunOrder**), and to simplify the experiment, the mix proportion number (**Table 4.2**) follows the run order.

4.1.2. Mix proportion

Based on the randomization in design of experiment, a series of mix proportion combination was prepared to study the effect of ultra fine fly ash content and different w/binder ratio on compressive strength of mortar. The mix proportion was prepared following standard test of mortar compressive strength, which has ratio sand to cement of 2.75 (ASTM C109/ C109M - 02., 2002). In this experiment, the term of sand to cement ratio was modified as sand to binder ratio.

The mix proportion was prepared with known specific gravity of material i.e. Portland cements 3.15, sand 2.59, water 1 and fly ash 2.64. In addition, 1% voids volume for 1 m^3 mortar was allowed in preparing the mix proportion to create a required volume of one cubic metre of mortar. As low w/binder ratio was used, this mix proportion needed high range water reducer (HRWR). The sodium naphthalene formaldehyde sulphonate with density of 1.2 kg/litre was used as HRWR. The result of four mix proportions of mortar is shown in **Table 4.3**.

Table 4.3: The mix proportions of mortar in design of experiment

Mix proportion	w/b ratio	Fly ash content	Cement (kg/m^3)	Fly ash (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Plasticizer ($litre/m^3$)
1	0.30	20%	462.1	115.5	173.3	1,558.4	9.0
2	0.35	50%	280.1	280.1	196.1	1,540.7	4.0
3	0.35	20%	451.1	112.8	197.4	1,550.7	8.0
4	0.30	50%	287.8	287.8	172.7	1,582.6	6.0

The mix proportion of mortar in design of experiment shows the higher use of w/b ratio leads to the increase of water volume in fresh mortar and results in lower amount of binder needed. Moreover, the total binder in the mix proportion is around 560 kg/m^3 and the superplasticizer content is between 4 – 9 $litres/m^3$. The difference of the total binder in each mix proportion is caused by the specific gravity of ultra fine fly ash which is less than the specific gravity of Portland cement. This makes the volume of ultra fine fly ash is higher than the volume of Portland cement at the same weight. Therefore, the more ultra fine fly ash is used the less the weight of binder is needed.

In addition, the higher the w/b ratio used leads to the higher water content in fresh mortar. Also, the higher water content leads to less need of the amount of plasticizer. Further decrease of the amount of plasticizer related to the increase of ultra fine fly ash content is caused by the spherical shapes of the fly ash particles that reduces the friction between cement and aggregates and results in an increase of workability of fresh concrete (Sata et al., 2007).

After the mix proportion and materials were ready, the mortar was batched in a mini mixer of five litres capacity and then it was cast in 50 x 50 x 50 mm cubes steel mould. All of the fresh mortars were compacted on a vibrating table to get better compaction. After the mortar specimens were cast, on the following day the mould was opened and the specimens were cured by placing them in the water tank with temperature around 25°C until the day of testing at 28 days and 56 days.

4.1.3. Compressive strength analysis

On the day of testing, the mortar specimens were removed from water tank to dry up and to measure the dimension. Afterwards, the compressive strength tests of the mortar were conducted using hydraulic MTS compression testing machine with loading rate of 50 kN/ minute (ASTM C109/ C109M - 02., 2002).

The compressive strength of mortar can be determined using the following equation:

$$f_m = \frac{P}{A}$$

where:

f_m = compressive strength (MPa)

P = total maximum load from the test (N)

A = area of loaded surface (mm^2)

The results of compressive strength are shown in **Table 4.4** and **Figure 4.3**.

Table 4.4: Compressive strength result for mortar

Mix proportion	fly ash content	w/binder ratio	Compressive strength (MPa)	
			28 days	56 days
1	20%	0.30	35.34	51.83
2	50%	0.35	32.81	47.46
3	20%	0.35	33.96	49.75
4	50%	0.30	33.69	48.20

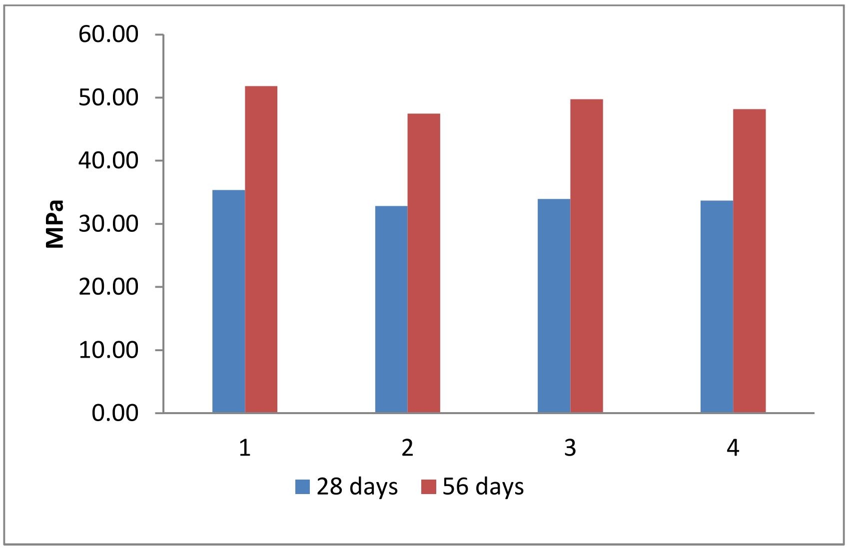


Figure 4.3: Compressive strength of mortar at 28 days and 56 days

To understand the influence of each factor in compressive strength of mortar, the results of compressive strength were analysed in Minitab. The result of the analysis using Minitab software comprises main effect plot, size of effect and interaction plot.

Worksheet 1 ***

↓	C1	C2	C3	C4	C5	C6	C7	C8
	StdOrder	RunOrder	CenterPt	Blocks	fly ash	w/b ratio	Compressive strength 28 d	
1	1	1	1	1	0.2	0.30	35.34	
2	4	2	1	1	0.5	0.35	32.81	
3	3	3	1	1	0.2	0.35	33.96	
4	2	4	1	1	0.5	0.30	33.69	
5								

Figure 4.4: Input for compressive strength analysed at 28 days

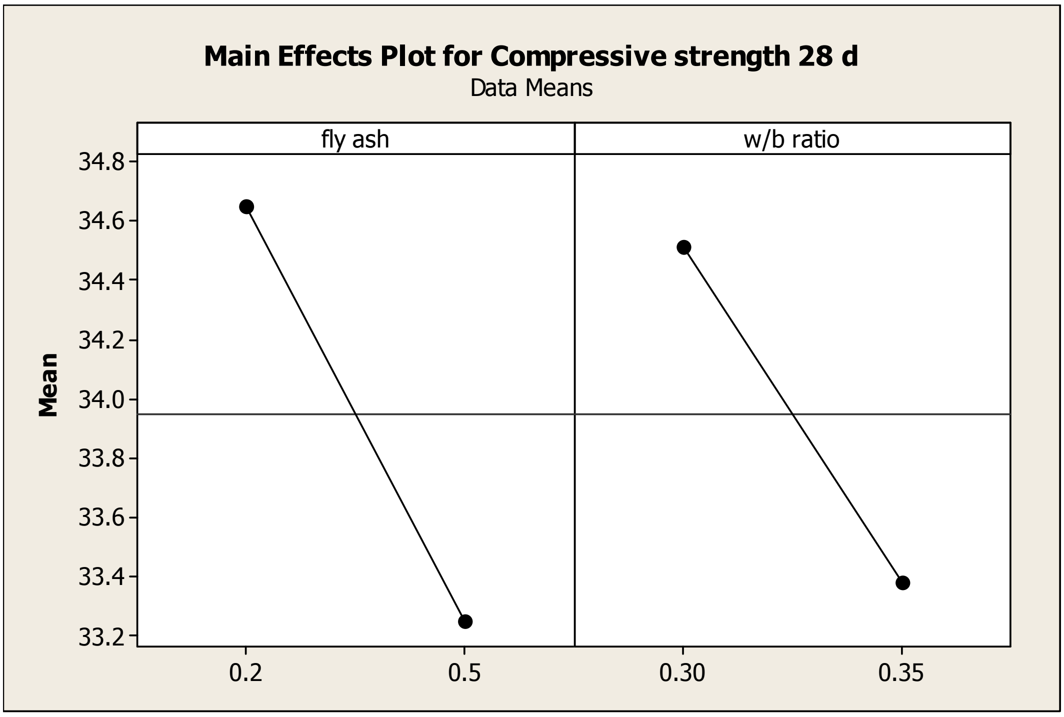


Figure 4.5: Main effect of compressive strength at 28 days

The main effect plot graph in **Figure 4.5** gives the same slope of linear curve for different ultra fine fly ash content and different w/b ratio on mortar's compressive strength, and it indicates that at the age of 28 days, ultra fine fly ash content and w/b ratio gave the same effect on compressive strength of mortar. Moreover, the effect of each factor can be calculated using the size of effect analysis, an analysis of the difference between the average response at the high level and the average response at low level.

Size of effect for ultra fine fly ash content:

$$\frac{(35.34 + 33.69)}{2} - \frac{(32.81 + 33.96)}{2} = 1.40$$

Size of effect w/b ratio

$$\frac{(35.34 + 33.96)}{2} - \frac{(32.81 + 33.69)}{2} = 1.15$$

The size of effect analysis result confirms that at 28 days there is no difference in effect of both ultra fine fly ash content and different w/b ratio on the compressive strength of mortars as they have relatively same size of effect. Interaction plot graph in **Figure 4.6** also confirms that there is no interaction between those two factors on compressive strength of mortar as can be seen in interaction plot graph (Antony, 2003).

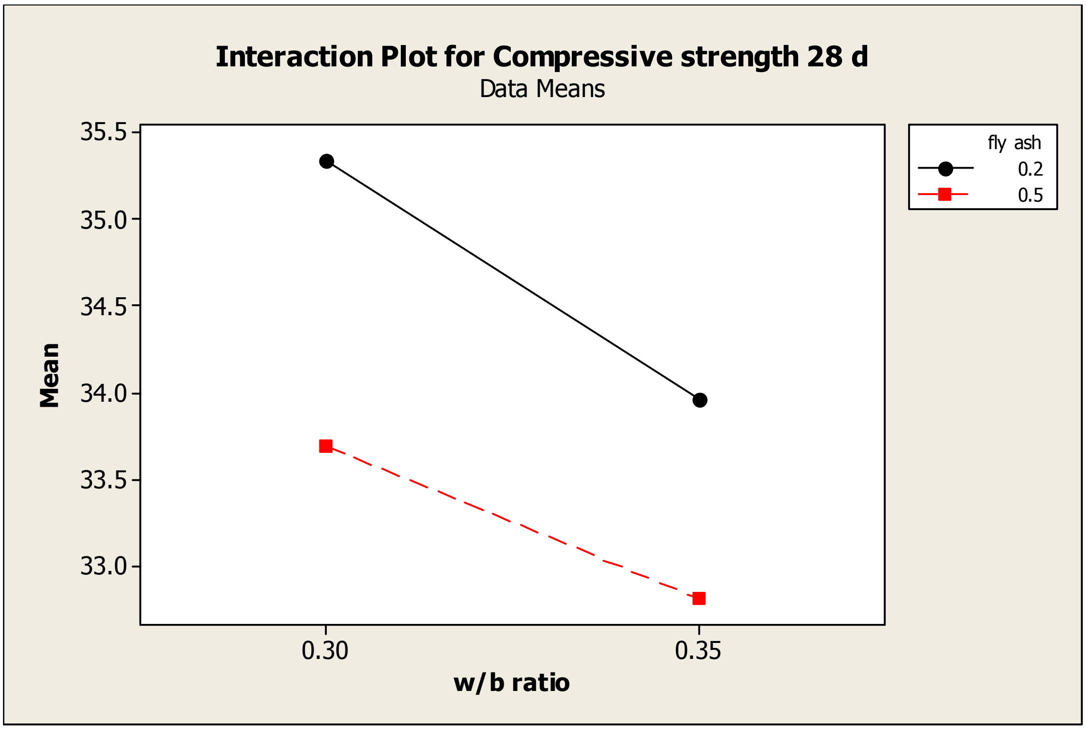


Figure 4.6: Interaction plot for compressive strength at 28 days

Similar to the analysis on main effect and interaction plot at the testing age of 28 days, the analyses were also conducted at the testing age of 56 days. The main effect plot graph (**Figure 4.8**) shows there is a different effect of both factors on the compressive strength of mortar as the linear curve slope of ultra fine fly ash content is higher in comparison to the slope of w/b ratio. The calculation of the size of effect gave the following result:

<u>Size of effect for ultra fine fly ash content:</u>

$$\frac{(51.83 + 49.75)}{2} - \frac{(47.46 + 48.20)}{2} = 2.90$$

<u>Size of effect w/b ratio</u>

$$\frac{(51.83 + 48.20)}{2} - \frac{(47.46 + 49.75)}{2} = 1.40$$

The size of effect analysis result confirms the main effect plot graph analysis that ultra fine fly ash content factor is more influencing on the compressive strength of mortar at the age of 56 days rather than w/b ratio factor in this study.

Worksheet 1 ***

↓	C1	C2	C3	C4	C5	C6	C7	C8
	StdOrder	RunOrder	CenterPt	Blocks	fly ash	w/b ratio	Compressive strength 56 d	
1	1	1	1	1	0.2	0.30	51.83	
2	4	2	1	1	0.5	0.35	47.46	
3	3	3	1	1	0.2	0.35	49.75	
4	2	4	1	1	0.5	0.30	48.20	
5								

Figure 4.7: Input for compressive strength analysed at 56 days

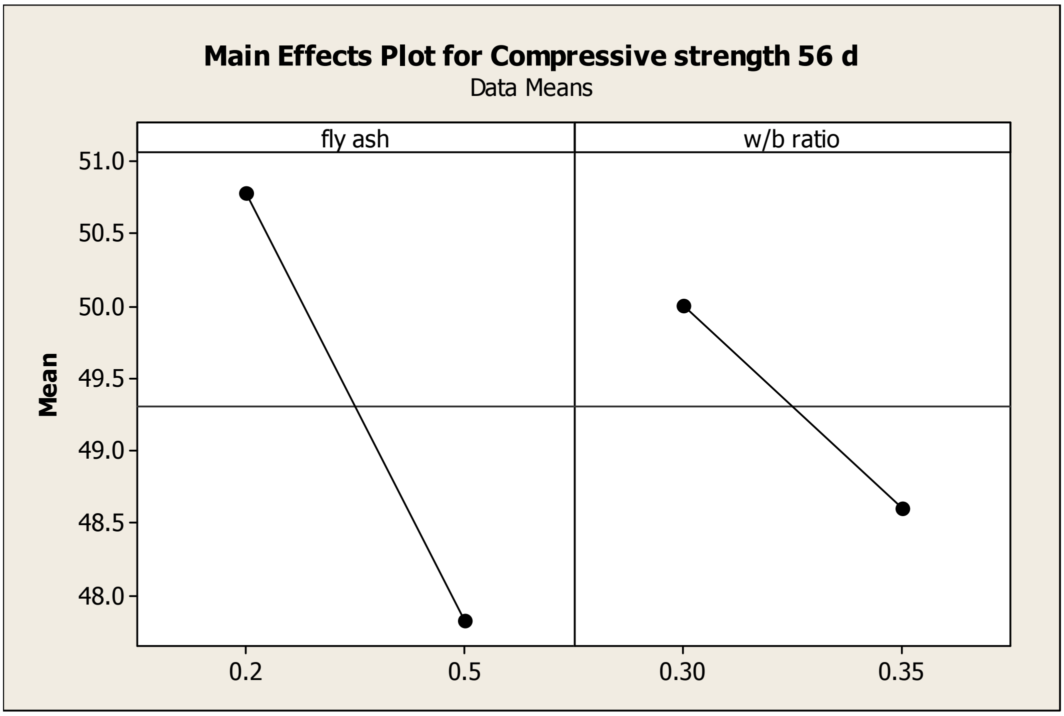


Figure 4.8: Main effect of compressive strength at 56 days

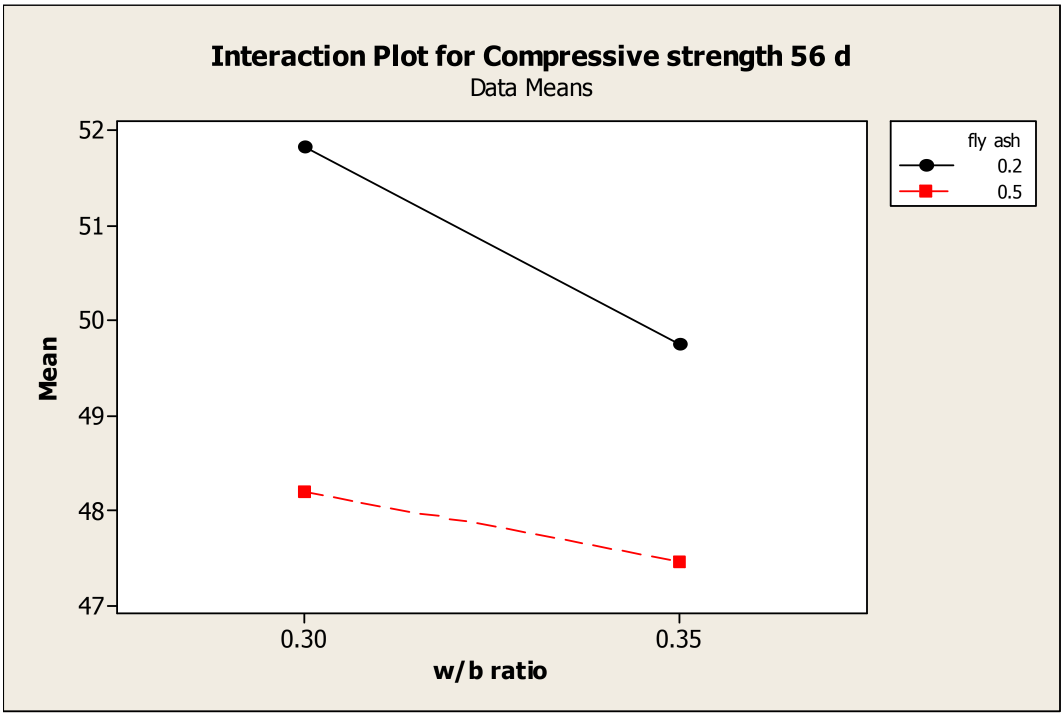


Figure 4.9: Interaction plot for compressive strength at 56 days

Both graphs of main effect plot for compressive strength at 28 (**Figure 4.5**) and 56 days (**Figure 4.8**) confirm that the highest mortar compressive strength was obtained when the low w/binder ratio combined with low ultra fine fly ash content were used in mix proportion. It is observed that the lowest strength was obtained in the mix proportion with high volume ultra fine fly ash content combined with high w/binder ratio. This result is in line with the former study as reported by Oner et al. (2005) which demonstrated that the compressive strength of fly ash concrete increases along with the increasing amount of fly ash up to an optimum value, and afterward, the strength starts to decrease with further addition of fly ash. In addition, lower w/b ratio is effective to improve concrete strength and concrete durability in high fineness of fly ash (Chalee and Jaturapitakkul, 2008).

Nevertheless, the decrease of mortar compressive strength from the low content of ultra fine fly ash to the high content of ultra fine fly ash content is not significant, only around 3-7%. In addition, for all mix proportions, the high strength mortar was obtained after the mortar was cured for 56 days.

The experiment on the effect of water binder ratio and ultra fine fly ash content on mortar compressive strength convincingly supports the hypothesis that high volume ultra fine fly ash can produce high strength concrete, however; longer period of water curing is needed (56 days).

4.2. Strength development of high volume ultra fine fly ash mortar

It has been mentioned in the previous experiment on the effect of water binder ratio and ultra fine fly ash content on compressive strength of mortar that by curing the mortar for 56 days there is a possibility to produce high strength mortar (minimum strength of 41 MPa) using high volume ultra fine fly ash. However, as the mix proportion for the mortar was based on sand to cement ratio of 2.75

(ASTM C109/ C109M - 02., 2002), the result of mortar compressive strength needs to be reanalysed when mix proportioning high strength concrete is used.

4.2.1. The use of saturated lime water in mortar mix proportion

The previous research reported that high volume fly ash concrete has slow strength development in comparison to OPC concrete, especially at early ages (Atis, 2003). To have the same strength development as OPC concrete, Elsageer et al. (2009) used elevated curing temperature up to 50^0C for high volume fly ash concrete. It has been mentioned that the increase of fly ash fineness to become ultra fine fly ash would be beneficial in increasing the reactivity of fly ash. However, high volume ultra fine fly ash still needs longer period of water curing and has lower compressive strength than OPC concrete (Sengul et al., 2005, Sengul and Tasdemir, 2009)

In addition, Mira P. et al. (2002) added hydrated lime in mix proportion of fly ash concrete to increase the $Ca(OH)_2$ substance, which is very important to react with silica in fly ash to produce C-S-H gel. Without the addition of the hydrated lime, the source of $Ca(OH)_2$ in fly ash concrete normally comes from cement hydration process, as can be seen in the following chemical reaction (Oner et al., 2005):

Cement hydration

$$\text{Cement } (C_3S;C_2S) + H_2O \rightarrow \text{CSH-gel} + Ca(OH)_2$$

Fly ash reaction:

$$Ca(OH)_2 \quad + SiO_2 \quad \rightarrow \text{CSH-gel}$$

The chemical reaction above shows high content of silica (SiO_2) in fly ash needs $Ca(OH)_2$ to react to form C-S-H gel. Hence, at this stage of research, it is beneficial to investigate the presence of saturated lime water to increase $Ca(OH)_2$ in mortar to make the source of $Ca(OH)_2$ come not only from cement hydration product but also from the contribution of saturated lime water which had reaction with silica (SiO_2) in fly ash.

The deployment of lime in treating concrete is also endorsed by ASTM which stated that lime water should be used as curing water for mortar cubes (ASTM C109/ C109M - 02., 2002).

However, although it is known that the use of lime in fly ash concrete improves the properties of concrete, there has not been any research on the use of lime water as mixing water in mortar. In addition, the use of saturated lime water also considered that the use of lime in liquid form in this study produced better reactivity with ultra fine fly ash than that of powder form as conducted by previous researchers (Ryan et al., 2007, Barbhuiya et al., 2009, Mira P. et al., 2002).

This use of saturated lime water to increase alkaline liquid in high volume ultra fine fly ash concrete is in line with geopolymer concrete production as stated by Davidovits (1999) that geopolymer concrete might be produced by making a reaction of alkaline liquid with silicon and the aluminum from by-product material (Lloyd and Rangan, 2010, Vijai et al., 2010).

4.2.2. Mortar mix proportion

The mortar mix proportion was prepared based on proposed method of high performance concrete mix design (Aïtcin, 2004) for 80 MPa design strength of concrete at the age of 28 days. As mortar only uses sand as aggregate, the method was modified by replacing total aggregate with only fine aggregate.

Besides, the amount of fine aggregate is important as adjustment to achieve the volume of one cubic meter of mortar.

The mix proportion was prepared using w/b ratio of 0.3 as lower w/b ratio gives higher strength of concrete. The specific gravity of materials are portland cement 3.15, coarse aggregate 2.80, sand 2.65, water 1, raw fly ash 2.01 and ultra fine fly ash 2.18.

The summary of mix proportion analysis for OPC mortar was shown in the following mix design sheet (**Figure 4.10**).

MIX DESIGN SHEET

Comp. Strength : 80 MPa

Table A	Spec. Gravity	%
Cement	**3.15**	**100.00%**
fly ash	**2.01**	**0.00%**
		0.00%

		%		
Aggregate	G_{SSD}	W_{abs}	W_{tot}	W_h
Coarse	**2.80**	**2.4**	**0**	-2.4
Fine	**2.65**	**3.9**	**1.5**	-2.4

$W_h = w_{tot} - w_{abs}$ $M = M_{SSD} \times (1 + w_h)$

Superplasticizer

G_{sup}	Solid dosage s (%)	$M_{sol} = C \times \frac{d}{100}$	$V_{liq} = \frac{M_{sol}}{s \times G_{sup}} \times 100$	$V_w = V_{liq} \times G_{sup} \times \left(\frac{100 - s}{100}\right)$	$V_{sol} = V_{liq} - V_w$
1.21	**40**	9.24	19.1	14.0	5.0

	1		2	3	4	5	6	
Materials	Content (kg/m³)		Volume (litre/m³)	Dosage SSD (kg/m³)	Water correction (litre/m³)	Composition (m3) 1 m³	**0.00165**	m³
w/b ratio	0.3							
water	165.00		165.00	165.00		192.0	0.3168	litre
cement	550	550	175.00	550.00		550.0	0.9076	kg
fly ash		0	0.00	0.00				kg
raw								
Coarse Agregate	1,000.00		357.00	1000.00	24.00	976.0	1.6105	kg
Fine aggregate			260.00	689.00	17.00	672.0	1.1089	kg
					Total aggregate =	**1,648.0**	**2.7194**	
Air	1.20%		12.00	0.00				
Superplasticizer	**1.68%**			9.00	-14.00	19.1	0.0315	litre
Total			714.00	2,413.00	27.00			

Figure 4.10: Mix design sheet for high strength OPC mortar

By using similar sheet in **Figure 4.10**, four mix proportions for testing high volume ultra fine fly ash mortar for its compressive strength development and flexural strength development were prepared. The mix proportions are:

a) Ordinary portland cement (OPC) using tap water as mixing water.

b) High volume raw fly ash using tap water as mixing water.

c) High volume ultra fine fly ash using tap water as mixing water.

d) High volume ultra fine fly ash using saturated lime water as mixing water.

The mix proportion of OPC mortar and high volume raw fly ash mortar were prepared as control mix proportion and the summary of mix proportion preparation for high volume fly ash mortar is shown in **Table 4.5**.

Table 4.5: Mortar mix proportion

Mix	Water	Cement (kg/m^3)	Fly ash (kg/m^3)	w/b ratio	Sand (kg/m^3)	HRWR (litre/m^3)
OPC mortar	Tap water	550.0	-	0.3	1,648.0	19.1
High volume raw fly ash (fly ash)	Tap water	275.0	275.0	0.3	1,529.0	14.5
High volume UFFA	Tap water	275.0	275.0	0.3	1,561.0	7.4
High volume UFFA lime water	lime water	275.0	275.0	0.3	1,561.0	7.4

The mix proportion of mortar shows that the weight of binder is the same for all mix proportion as the w/binder ratio for all of mix proportions are same. However, as the density of raw fly ash and ultra fine fly ash are lower from Portland cement, the volume of binder will be different and it influences the volume of sand. Moreover, the use of high volume fly ash significantly decreases the amount of superplasticizer used in comparison to OPC and further decrease of 61% arises when high volume ultra fine fly ash is used.

In addition, the sand content in the mix proportion was used to adjust the volume in order to achieve the volume of 1 m^3 of mortar mix proportion. Hence, the use of high volume fly ash which has higher volume than portal cement in the same weight will reduce the sand content. However, the decrease of the use of superplasticizer in fly ash mortar made the mix proportion need more sand to achieve same volume of 1 m^3 mortar..

After the mix proportion and materials were ready, the mortar was batched in mini mixer of five litre capacity and then it was cast in 50 x 50 x 50 mm cube steel moulds for compressive strength test and cast in 40 x 40 x 160 mm prism moulds for flexural strength test.

Figure 4.11: Materials, mini mixer and mould for casting mortar specimens

In mixing the materials, to start with, the binder was mixed first then the sand was added for dry mix. Afterward, the water was added and the superplasticizer was adjusted to have suitable consistency. When pouring the fresh mortar into the mould, all of them were compacted on vibrating table to get better compaction. After the mortar specimens were cast, on the following day the mould was opened and the specimens were cured by placing them in the water tank with temperature approximately 25°C until the day of testing at 7days, 14 days, 21 days, 28 days and 56 days.

4.2.3. Compressive strength development of mortar

On the day of compressive strength test, the mortar specimens were removed from water tank to dry up and to measure the dimension. The compressive strength tests of the mortar were conducted using hydraulic compression testing machine (MTS) using loading rate of 50 kN/ minute (ASTM C109/ C109M - 02., 2002). For every mix proportion variation and every single testing age, the compressive strength was calculated from the average of five specimens provided.

Figure 4.12: Mortar compressive strength

The result of compressive strength development for all four mix proportions and strength development are presented in **Table 4.6** and **Figure 4.13.**

Table 4.6: Compressive strength of mortar

Mix	Compressive strength (MPa) at				
	7 d	14 d	21 d	28 d	56 d
OPC mortar	33.30	40.14	43.26	46.28	49.00
High volume raw fly ash	15.19	24.62	28.35	34.06	39.33
High volume UFFA	26.17	33.42	36.04	40.28	45.31
High volume UFFA lime water	32.88	39.73	44.03	49.38	57.13

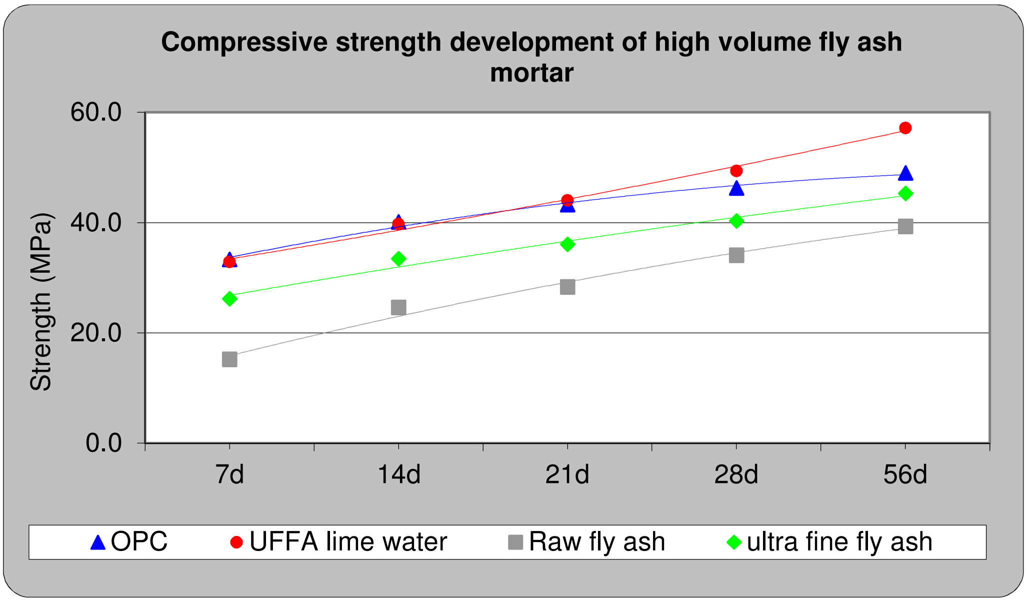


Figure 4.13: Compressive strength development of mortar

The mortar compressive strength for all the mix proportion combinations shows the compressive strength of mortar increases along with the increase of curing age especially for all high volume fly ash mortars. Different trend happens to the compressive strength of OPC mortars which only increases slightly from the testing age of 28 days to 56 days.

In addition, all of the mortar has lower compressive strength than concrete mix design strength of 80 MPa at 28 days. The lower compressive strength of the mortar than mix design compressive strength might be caused by the mortar which merely uses sand for its aggregate and the absence of coarse aggregate in mortar significantly decreases the compressive strength of mortar (Cong et al., 1992).

However, OPC mortar and high volume ultra fine fly ash using lime water as mixing water can reach high compressive strength of 41 MPa which starts at the age of 28 days. Moreover, high volume ultra fine fly ash mortar using tap water as mixing water can reach high compressive strength mortar after 56 days of curing. It is observed that the high volume raw fly ash mortar cannot reach the high strength up to testing age of 56 days.

In addition, the compression strength of the mortars increases as the testing age is longer except for OPC mortar which has similar compressive strength at both the ages of 28 days and 56 days.

In comparison to OPC mortar, the use of both high volume raw fly ash and high volume ultra fine fly ash using tap water as mixing water reduces the compressive strength of mortar, especially at early ages. The reduction of compressive strength of mortar which is caused by the use of high content of fly ash is similar to that reported by another researcher (Yılmaz and Olgun, 2008). Besides, the low strength at early ages of fly ash concrete caused by a slower pozzolanic reaction of fly ash confirms the study from Fraay et. al (1989).

After longer period of curing and in comparison to OPC mortar, the decrease of compressive strength of high volume fly ash mortar and high volume ultra fine fly ash mortar is lower compared to that at early ages. At the age of 7 days the compressive strength of high volume raw fly ash mortar and high volume ultra fine fly ash mortar is reduced by 54.4% and 21.4% respectively, whereas at the age of 56 days, the reduction of compressive strength is 18.9% and 6.6% respectively.

The significant findings in mortar experiment is the use of saturated lime water as mixing water in high volume ultra fine fly ash which gives significant contribution to mortar compressive strength development. At early ages, the compressive strength of mortar is similar to that of OPC mortar. Moreover, at the ages of 28 days and 56 days the compressive strength of high volume ultra fine fly ash mortar with lime water is higher than that of OPC mortar. The increase of compressive strength in high volume ultra fine fly ash mortar using saturated lime water is 6.7% and 17.7% at the age of 28 days and 56 days respectively compared to that of OPC mortar.

In view of increasing compressive strength and comparing high volume ultra fine fly ash mortar using saturated lime water to that using tap water, it is remarkable to note that the contribution of using saturated lime water is quite significant to increase the compressive strength. Former research using lime putty as addition to fly ash concrete with the amount of 5%, 10%, 15%, 20% and 25% by cement weight did not give significant improvement on compressive strength in comparison to fly ash concrete without lime putty (Mira P. et al., 2002). The small increase in compressive strength in previous research might be caused by the high content calcium in the fly ash. Another study by Barbhuiya, et. al. (2009) which used fly ash with low content of calcium in high volume fly ash concrete showed that the lime addition of 5% increases significantly the compressive strength of concrete in comparison to the high volume fly ash without lime. Nevertheless, the strength result did not include OPC concrete as a control mix.

The result of compressive strength provides evidence that the presence of saturated lime water as mixing water increases the alkalinity of the water at the amount needed to react with silica (SiO_2) in high volume ultra fine fly ash mortar to give contribution to compressive strength starting at early ages (Fraay et al., 1989).

4.2.4. Flexural strength of mortar

Similar to compressive strength, the flexural strength test of mortar was carried out at the curing ages of 7 days, 14 days, 21 days, 28 days and 56 days. The test was conducted on prismatic specimens of 40 x 40 x 160 mm using three point loading tests. By using the test setup, the distance between supports was kept 120 mm and the point load was placed in the center of mortar prism.

The load was applied using hydraulic compression testing machine (MTS) with loading rate of 2.65 kN/ minute (ASTM C 348 – 02., 2002) until the maximum load. For every mix proportion variation and each testing age, the compressive strength was calculated from the average of five specimens provided.

Figure 4.14: Mortar flexural strength test

Based on the maximum load recorded, for the mortar prism of 40 x 40 x 160 mm, the flexural strength of mortars was calculated using the following equation:

$S_f = 0.0028\ P$

where:

S_f = flexural strength (MPa)

P = total maximum load (N)

The flexural strength development of the mortar is shown in **Table 4.7** and **Figure 4.15**.

Table 4.7: Flexural strength development of mortar

Mix	Flexural strength (MPa) at				
	7 d	**14 d**	**21 d**	**28 d**	**56 d**
OPC mortar	5.95	7.02	7.39	7.51	7.61
High volume raw fly ash	4.08	4.46	4.94	5.83	6.27
High volume UFFA	5.86	5.95	6.74	7.49	7.59
High volume UFFA lime water	5.40	5.42	6.50	7.55	7.69

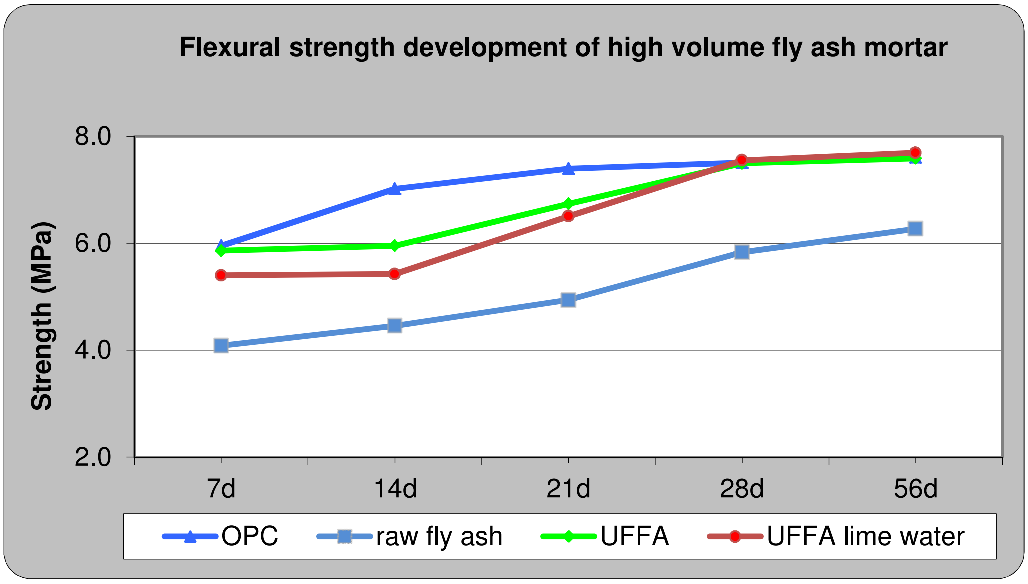


Figure 4.15: Flexural strength development of mortar

The mortar flexural strength development result shows the flexural strength of mortar increases along with the increase of curing age of the mortar up to 28 days. At the age of 28 days and 56 days the flexural strength of the mortar is similar except for high volume raw fly ash mortar which still slightly increases its flexural strength.

The OPC mortar has faster flexural strength development to the test age of 56 days in comparison to high volume fly ash mortar which has lower flexural strength development. This finding is supported by earlier study who reported that the increase of fly ash content will reduce flexural strength of mortar (Paya et al., 1995, Shi and Kan, 2009, Wong et al., 1999).

However, after 28 days of curing the flexural strength for high volume ultra fine fly ash mortar using tap water or saturated lime water as mixing water for mortars are comparable to that of OPC mortar. It shows that ultra fine fly ash has better pozzolanic reactivity than raw fly ash.

It is important to note here that there is different result between compressive strength development and flexural strength development of high volume ultra fine fly ash mortar with saturated lime water as mixing water in comparison to OPC mortar. At early ages, the flexural strength development is lower, while the compressive strength development is similar to that in OPC mortar. Furthermore, at 56 days, the compressive strength is higher than that in OPC mortar while the flexural strength in both high volume ultra fine fly ash mortar and OPC mortar is similar.

4.2.5. Water absorption of mortar

Water absorption of mortar test was conducted based on Australian Standard (AS 1012.21., 1999) to study moisture transport in cement mortar (Kim et al., 2012). The test was carried out after the curing age of mortar at 56 days. There are two kinds of absorptions tested, i.e. immersed water absorption and saturated water absorption. In addition, the apparent volume of permeable voids (AVPV) was also determined.

Figure 4.16: Mortar cubes immersion for 2 days

Figure 4.17: Weight measurement of mortar

Immersed absorption measured the absorption of water after soaking the specimen in water for 2 days while saturated absorption measured the absorption of water when the specimen was in saturated state. In saturated absorption, preparing specimen for rapid chloride penetration testing method (ASTM C 1202 - 97., 2002) was used in saturating the specimen. By using this method, the specimen was vacuumed for three hours before soaking into water for 18 hours.

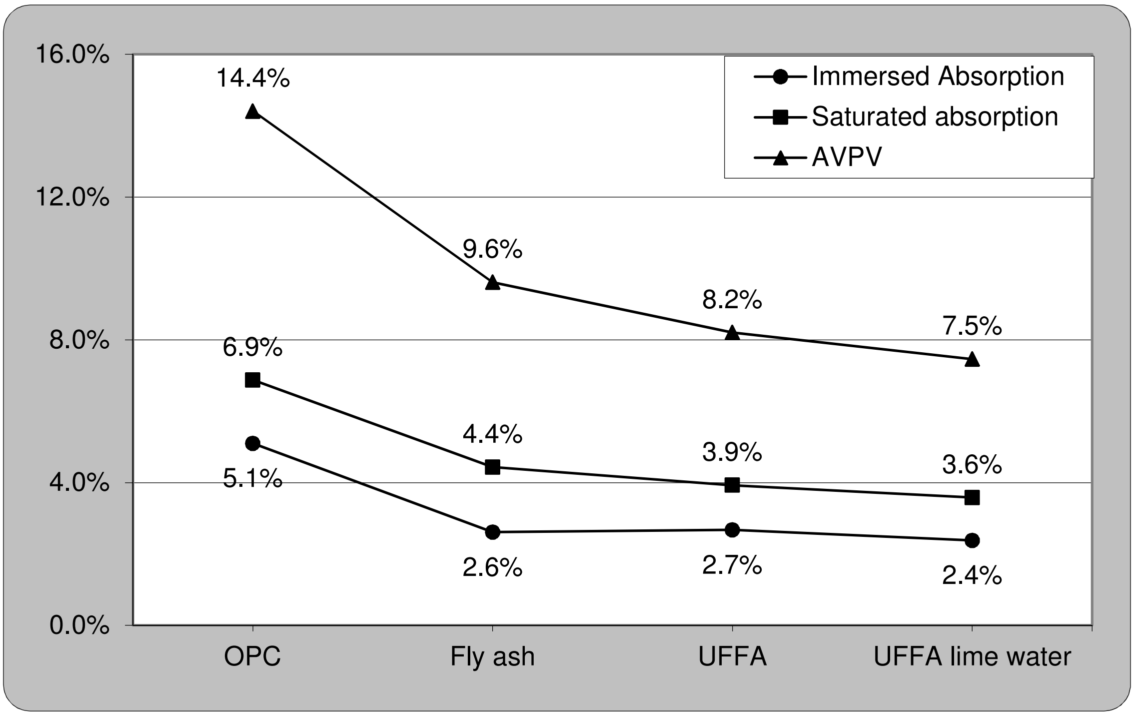


Figure 4.18: Water absorption of mortar

The result of water absorption shows that the use of high volume fly ash significantly reduces water absorption and apparent volume of permeable voids in mortar in comparison to OPC mortar (**Figure 4.18**). The decrease of water absorption in high volume raw fly ash using tap water as mixing water is 48.8% and 35.5% for immersed absorption and saturated absorption respectively. Also, the decrease of water absorption in high volume ultra fine fly ash using tap water as mixing water is 47.6% for immersed absorption and 42.9% for saturated absorption. Moreover, the decrease of water absorption in high volume ultra fine fly ash using lime water as mixing water is 53.3% and 47.9% for immersed absorption and saturated absorption respectively.

The result of immersed absorption and saturated absorption indicate that the mortar produced using high volume fly ash either using tap water or saturated lime water has higher compactness than OPC mortar. Similarly, Iyer R.S. and Stanmore B (1999) also reported, the decrease of water absorption related to the increase of fly ash fineness.

In term of concrete durability, the apparent volume of permeability voids (AVPV) becomes one of the indicators to classify the level of concrete durability (Technical roads 89, 2007). Based on the criteria for vibrated cylinders (**Table 4.8**), all of the high volume fly ash mortars have excellent level of durability. Nevertheless, with the AVPV of 14.4% OPC mortar has marginal criteria of durability.

Table 4.8: Classification of concrete durability level, based on the AVPV (CCAA Report, 2009)

Durability classification indicator	**Vibrated cylinders** (AVPV %)	**Rodded cylinders** (AVPV %)	**Cores** (AVPV %)
1. Excellent	< 11	< 12	< 14
2. Good	11 – 13	12 – 14	14 – 16
3. Normal	13 – 14	14 – 15	16 – 17
4. Marginal	14 – 16	15 – 17	17 – 19
5. Bad	> 16	> 17	> 19

The durability criteria based on the apparent volume of permeable voids would be confirmed when testing durability of concrete.

4.3. Summary of Chapter 4

The result of investigation on the strength of high volume ultra fine fly ash mortar can be summarized as follow:

1) The use of high volume ultra fine fly ash as cement replacement enables the production of high strength mortar.

2) The production of high volume-high strength ultra fine mortar needs low water/binder ratio of 0.3 as well as longer period of curing (56 days).
3) The use of saturated lime water as mixing water in high volume ultra fine fly ash mortar can produce mortar which has same compressive strength development as OPC mortar at early ages.
4) At 56 days of curing, the use of saturated lime water as mixing water in high volume ultra fine fly ash mortar can achieve higher compressive strength in comparison to OPC mortar.
5) Water absorption properties of high volume fly ash mortar and high volume ultra fine fly ash mortar is lower than that of OPC mortar.

Having investigated the strength of high volume ultra fine fly ash, this research continues to investigate the properties of high volume ultra fine fly ash concrete wherein water curing period of 56 days was applied, lime water was used as mixing water and basalt fibre was used as strengthening material.

5. Mechanical properties of High strength concrete with high volume ultra fine fly ash reinforced with Basalt fibre

5.1. Overview

The previous investigation on mortar strength of high volume ultra fine fly ash has confirmed the possibility of producing high strength concrete using high volume ultra fine fly ash as cement replacement. Furthermore, the benefit of using saturated lime water as mixing water to increase compressive strength of high volume ultra fine fly ash mortar was also confirmed. Moreover, to achieve better strength development, high volume ultra fine fly ash mortar needs water curing for 56 days.

In addition, generally the ductility of high strength concrete is lower than the ductility of normal strength concrete and it is possible to develop catastrophic and sudden failure in particular when the structure subject to explosive load (Ramakrishnan et al., 1981). Therefore, this weakness needs to be balanced by adding some fibre into the mix (Ashour et al., 1992, Taylor et al., 1997). This research employed basalt fibre as strengthening material for high strength concrete using high volume ultra fine fly ash. The use of basalt fibre in concrete will be useful as basalt fibre has higher modulus of elasticity, has higher chemical stability, and has tensile strength twice more than that of E-glass fibres (Ramakrishnan et al., 1998). Besides, although basalt fibre lost their volume and strength after immersing in alkali solution the fibre has good resistance when being exposed to high temperature (Sim et al., 2005).

Since the high strength concrete was produced by using selected materials, the replacement of high volume of cement with ultra fine fly ash and the use of low w/binder ratio in mix proportion would make the concrete have high performance concrete properties. This chapter investigates mechanical properties of the high strength concrete by testing workability, compressive strength development, and modulus of rupture development. In addition, the modulus of elasticity of high strength concrete was also investigated.

5.2. Mix proportions of High strength concrete

5.2.1. Design of experiment

This research employed three important factors in producing high strength concrete, i.e. type of fly ash, kind of mixing water and the utilization of basalt fibre as strengthening material. Although previous investigation in mortar properties showed the higher strength of mortar was resulted from combination of using high volume of ultra fine fly ash and saturated lime water in mortar mix proportion, concrete has different aggregate composition and need larger material than mortar. For that reason, the investigations for utilization of each material on mechanical properties of concrete were conducted.

Each of observed factors consists of two level values needed to be considered in giving contribution to mechanical properties of high strength concrete. The two levels of fly ash are the use of high volume raw fly ash and the use of high volume ultra fine fly ash as cement replacement. In addition, the two levels of mixing water in concrete are the use of tap water and the use of lime water. Moreover, the two levels of basalt fibre are the use of basalt fibre in high strength concrete and high strength concrete without basalt fibre.

It is important to note here that the lime water was made by mixing 50% of saturated lime water and 50% of tap water. The reason of using only 50% of saturated lime water as mixing water was to avoid stiff consistency in fresh concrete. The stiff consistency might happen as the use of lime water as mixing water in fly ash concrete is similar to the method of geopolymer concrete production in which a reaction of alkaline liquid with silicon and aluminium from by-product material is used (Davidovits, 1999, Vijai et al., 2010). The previous research showed that geopolymer concrete has a solid consistency in fresh state (Rangan et al., 2006).

The three factors and its level in design of experiment are shown in **Table 5.1.**

Table 5.1: The factor and the level in design of experiment

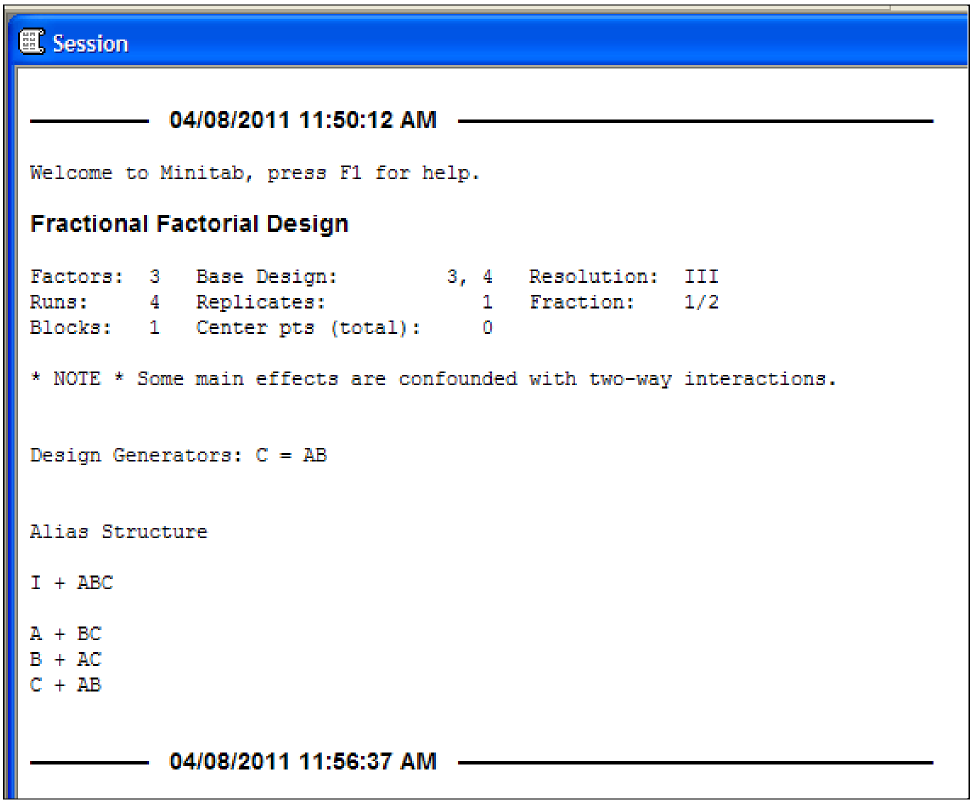
Factor	Low	High
Type of fly ash	Ultra fine fly ash (UFFA)	Raw fly ash
Kind of water	Lime water	Tap water
The used of fibre	Basalt fibre	No fibre

To understand the effect of each factor in mechanical properties of high strength concrete and to draw a valid conclusion, the preparation of mix proportions and also data analysis were conducted using design of experiment. The design of experiment was used for analysing effect of type of fly ash, kind of mixing water and the utilization of basalt fibre as strengthening material on compressive strength and modulus of rupture of high strength high volume ultra fine fly ash concrete. Moreover, to maintain the accurate result, MINITAB software was used to perform design of experiment.

To prepare the mix proportion of high volume ultra fine fly ash concrete, the observed factors with their levels need to be randomly distributed in all experiment combinations. In addition, the order of experiments also needs to be randomly performed. The randomization is common and very important in experimental design to reduce the systematic bias that influences the experiment. (Antony, 2003)

If full factorial design was used to randomize those three factors which consist of two levels for each factors, it will result in $2^k = 2^3 = 8$, eight possible combinations need to be analysed. However, as it is not easy to afford all of the combination in concrete experiment, half (½)fraction factorial design was used which resulted in four combinations of those factor which neglect higher order interaction between factor and levels (Montgomery, 2009).

The randomization of those factors was conducted under design of experiment half fractional factorial design section. The result of randomization of three observation factors of type of fly ash, kind of mixing water, and the utilization of basalt fibre as strengthening material each of which consist of two levels is shown in **Figure 5.1, Figure 5.2,** and **Table 5.2.**


Session

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Welcome to Minitab, press F1 for help.
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Fractional Factorial Design

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Factors:  3   Base Design:         3, 4   Resolution:  III
Runs:     4   Replicates:             1   Fraction:    1/2
Blocks:   1   Center pts (total):     0

* NOTE * Some main effects are confounded with two-way interactions.


Design Generators: C = AB


Alias Structure

I + ABC

A + BC
B + AC
C + AB
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Figure 5.1: Randomly session in MINITAB's session

Worksheet 1 ***

↓	C1	C2	C3	C4	C5-T	C6-T	C7-T	C8
	StdOrder	RunOrder	CenterPt	Blocks	Fly ash	Water	Fiibre	
1	4	1	1	1	UFFA	Tap water	No fibre	
2	2	2	1	1	UFFA	Lime water	Basalt fibre	
3	3	3	1	1	Raw	Tap water	Basalt fibre	
4	1	4	1	1	Raw	Lime water	No fibre	
5								

Figure 5.2: The result of randomization in MINITAB's worksheet

Table 5.2: The randomization of a one-half fraction of 2^3 designs

Combination	Fly ash	Mixing water	Fibre
I	UFFA	Tap water	No Fibre
II	UFFA	Lime water	Basalt fibre
III	Raw	Tap water	Basalt fibre
IV	Raw	Lime water	No Fibre

Using the randomization technique, those observed factors with their level in experiment are assured to be well distributed in all of mix proportion, and therefore; the valid conclusion will be achieved.

5.2.2. Mix proportion of high strength concrete

Based on the randomization of those three factors, four mix proportions were prepared (**Table 5.3**). The mix proportion of concrete was based on proposed method of high performance concrete mix design (Aïtcin, 2004) for design compressive strength of 80 MPa at 28 days to create 1m^3 of concrete. The mix proportion was made using specific gravity of Portland cement of 3.15, fine aggregate of 2.60, coarse aggregate of 2.89, raw fly ash of 2.01 and ultra fine fly ash of 2.18. In addition, the basalt fibre has specific gravity of 2.67.

As the high performance concrete needs low w/binder ratio, this mix proportion needed high range water reducer (HRWR). The HRWR used was sodium naphthalene formaldehyde sulphonate (Sikament NN) from SIKA Australia with density of 1.2 kg /litre.

Table 5.3: Mix proportion of high strength high volume fly ash concrete

Mix proportion	Cement (kg/m3)	Fly ash (kg/m3)	Water (kg/m^3)	Agregate		HRWR ($litre/m^3$)	Basalt Fibre (kg/m^3)
				Fine (kg/m^3)	Coarse (kg/m^3)		
UFFA without basalt fiber, tap water (No 1)	225.0	225.0	141.0	835.0	994.0	7.0	-
UFFA with basalt fiber, lime water (No 2)	225.0	225.0	141.0	809.0	994.0	7.0	26.7
Raw Fly Ash with basalt fibre, tap water (No 3)	225.0	225.0	139.0	785.0	994.0	10.2	26.7
Raw Fly Ash without basalt fibre, lime water (No 4)	225.0	225.0	139.0	811.0	994.0	10.2	-

The total binder in the mix proportion is 450 kg/m^3 with the water/ binder ratio of 0.3. Although all the mix proportions use same w/b ratio, high volume ultra fine fly ash (UFFA) needs less amount of high range water reducer (HRWR) in comparison to high volume raw fly ash. Also, the HRWR has 60% content of liquid and therefore the more HRWR is used the less the amount of water is needed. The decrease of water demand related to the use fly ash and further decrease of water demand related to the processing of raw fly ash to become fine fly ash are in line with earlier research (ACI 232.2R-03, 2003, Obla et al., 2003).

Moreover, the basalt fibre content was 1% of total concrete volume of 1 m^3. With the specific gravity of 2.67, each mix proportion needs 26.7 kg of basalt fibre per m^3 of concrete. The presence of basalt fibre will adjust the amount of fine aggregate in concrete.

In addition to the mix proportion of high volume fly ash concrete, the control mix proportion of high strength OPC concrete was also prepared which consists of three mix proportions. Beside the high strength OPC concrete, another two mix proportions were also prepared. The first one used basalt fibre and the second one used steel fibre as strengthening materials **(Table 5.4)**.

Table 5.4: Mix proportion of OPC concrete as control mix proportion

Mix proportion	Cement	Water	Agregate		HRWR	Fibre
			fine	Coarse		
	(kg/m3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(litre/m^3)	(kg/m^3)
OPC without fibre, tap water (No 5)	450.0	137.0	912.0	994.0	13.9	-
OPC with basalt fibre, tap water (No 6)	450.0	136.0	887.0	994.0	13.9	26.7
OPC with steel fibre, tap water (No 7)	450.0	136.0	888.0	994.0	13.9	75.0

Control mix proportion of high strength concrete was also prepared using w/c ratio of 0.3. However, in comparison to high volume fly ash concrete, OPC concrete needs more HRWR. In addition, the presence of basalt fibre and steel fibre in concrete mix proportion made the amount of fine aggregate need to be adjusted to achieve concrete volume of 1m^3.

Each concrete mix proportion was batched in mixer with capacity of 100 litres and then it was cast in cylinder of ϕ100 mm x 200 mm height mould and prism of 100 x 100 x 350 mm mould. When casting the fresh concrete into the mould, the concrete was compacted using vibrating table to get better density. Also, the slump test was conducted to observe the workability of fresh concrete.

Figure 5.3: Mixer and vibrating table for casting the concrete

On the following day after casting the concrete, the specimens were taken out from the mould and the specimens were cured by placing them in the water tank with temperature of 24°C for 56 days. After 56 days in water curing tank the specimens were removed and placed on specimen shelf under room temperature until the last day of the test at the age of 180 days.

5.2.3. Slump test

Slump test is the most universal workability test of fresh concrete which measures the consistency of concrete (Mehta and Monteiro, 2006). The test employs a truncated cone with the dimension of 300 mm height, and 100 mm diameter on the top and 200 mm diameter on the bottom (**Figure 5.4**).

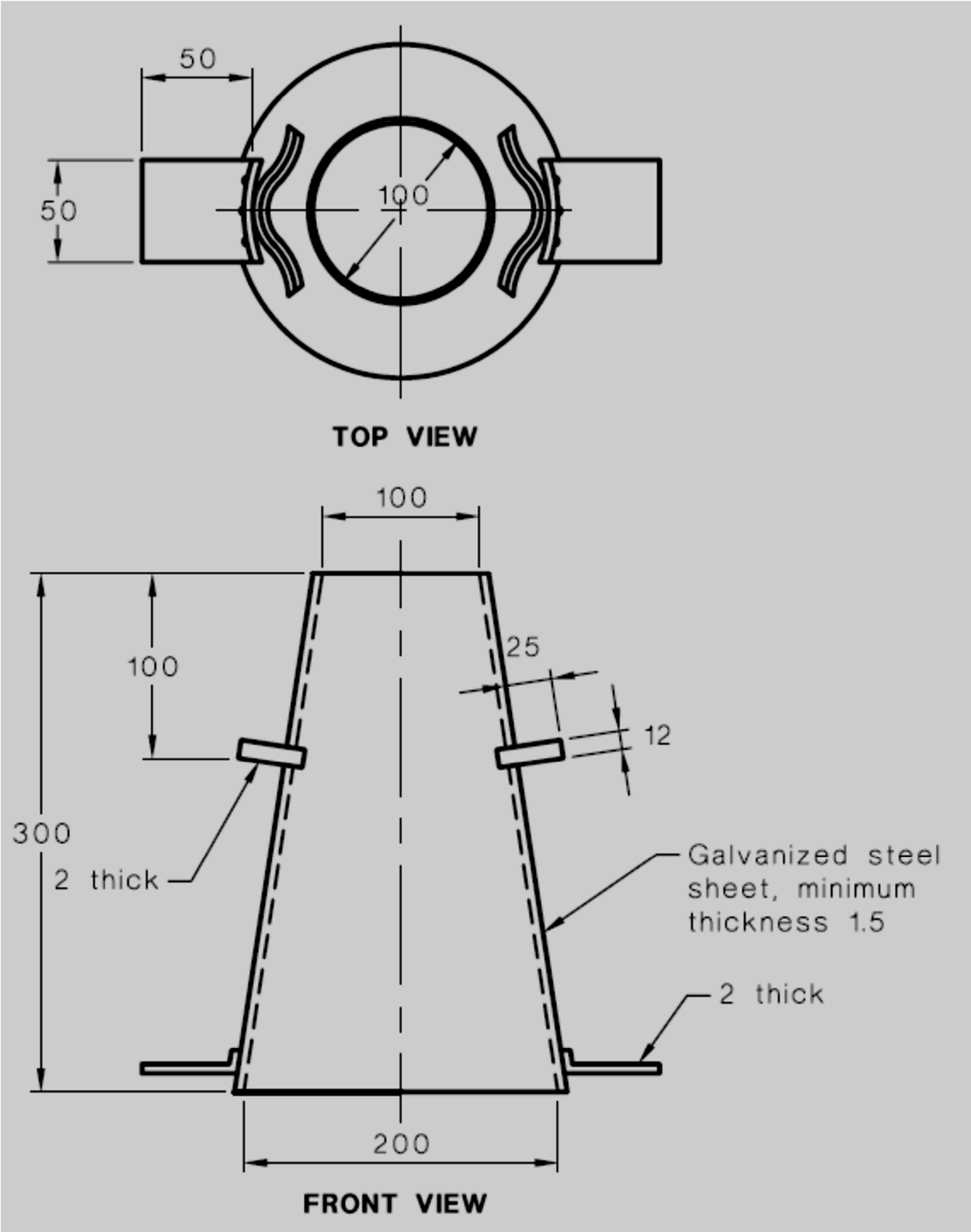


Figure 5.4: A truncated cone for slump test (AS 1012.3.1, 1998)

Figure 5.5: Slump test of the concrete

Table 5.5: The result of slump test

No.	Mix proportion	Slump test
1	UFFA without basalt fiber, tap water (No 1)	70.0 mm
2	UFFA with basalt fiber, lime water (No 2)	75.0 mm
3	Raw Fly Ash with basalt fibre, tap water (No 3)	52.5 mm
4	Raw Fly Ash without basalt fibre, lime water (No 4)	no slump
5	OPC without fibre, tap water (No 5)	35.0 mm
6	OPC with fibre, tap water (No 6)	50.0 mm
7	OPC with steel fibre, tap water (No 7)	50.0 mm

The slump test results (**Table 5.5**) shows that the high performance concrete satisfies the slump requirement for high strength concrete. The high strength OPC concrete mix proportions has low slump between 35 mm to 50 mm and based on ACI report on high strength concrete, the kind of slump usually is allowed in precast operations (up to 2 inches) although it would need special technique of compaction (ACI 363R-92., 1997). However, as the concrete for this research was cast in laboratory and compacted using vibrating table, the consolidation of concrete is well achieved.

In addition, for high volume fly ash concrete, the value of the slump is higher in comparison to that of OPC concrete slump, between 52.5 mm to 75 mm. The slump value is in the range of cast in place concrete criteria (between 64 and 114 mm) according to ACI report on high strength concrete (ACI 363R-92., 1997). The higher slump for high volume fly ash was caused by the increase of concrete workability due to the spherical fly ash particle which was also reported by some researchers (Atis and Karahan, 2009, Bouzoubaâ et al., 1999, Idorn and Henriksen, 1984).

Moreover, one of the mix proportion experienced slump loss (mix proportion no 4) which was possibly caused by higher moisture content in aggregate. However, as the water used did not exceed the water which was prepared in mix proportion therefore the casting of concrete was continued.

It is important to note here that the use of lime water in fly ash concrete made different property of fresh concrete related to the slump result. Although the slump of fly ash concrete using lime water is same as the slump test of fly ash concrete using tap water, however the lime water made the fresh concrete of fly ash concrete was observed to be sticky. This result is similar as fresh concrete of geopolymer concrete (Rangan et al., 2006), since the use of lime water as mixing water for high volume fly ash concrete adopt the method to produce geopolymer concrete.

5.3. Compressive strength and modulus of rupture of high strength concrete

5.3.1. Compressive strength development of fly ash concrete

The compressive strength tests of the concrete were carried out at the concrete ages of 28 days, 56 days, 84 days, and 180 days to find its compressive strength development. As all of the concretes specimens were cured for 56 days, the 28 days and 56 days compressive strength test was carried out when the specimen was still in curing process. One day before the day of test, the cylinder was taken out from the curing tank and the top surface was cut using wet diamond saw cutter machine to get the flat surface.

The compressive strength test machine with a maximum capacity of 900 kN was used for testing the compressive strength of concrete. Based on Australian standard for compressive strength test (AS 1012.9, 1999) the loading rate for the compressive strength test was 20 ± 2 MPa/min and with the cylinder's area of 7,853 mm^2 it is equal to 157 kN/min. The load was applied until maximum load of concrete cylinder and the compressive strength was calculated by dividing the maximum load to failure by the average cross-sectional area (Kett, 2000).

Table 5.6 and **Figure 5.6** show compressive strength development of high volume fly ash concrete which was prepared based on design of experiment's mix proportion. In addition, compressive strength of high strength OPC concrete without fibre is also presented as control mix proportion. The compressive strength is calculated from the average of 3 specimens.

Table 5.6. Compressive strength development of High volume fly ash concrete

	Compressive strength (MPa)			
	28 d	**56 d**	**84 d**	**180 d**
UFFA without basalt fiber, tap water (No 1)	70.90	74.72	91.94	94.90
UFFA with basalt fiber, lime water (No 2)	73.78	78.84	89.45	92.25
Raw Fly Ash with basalt fibre, tap water (No 3)	52.97	57.23	67.28	71.06
Raw Fly Ash without basalt fibre, lime water (No 4)	66.69	71.97	81.95	85.82
OPC without fibre, tap water (No 5)	79.44	84.51	93.68	95.36

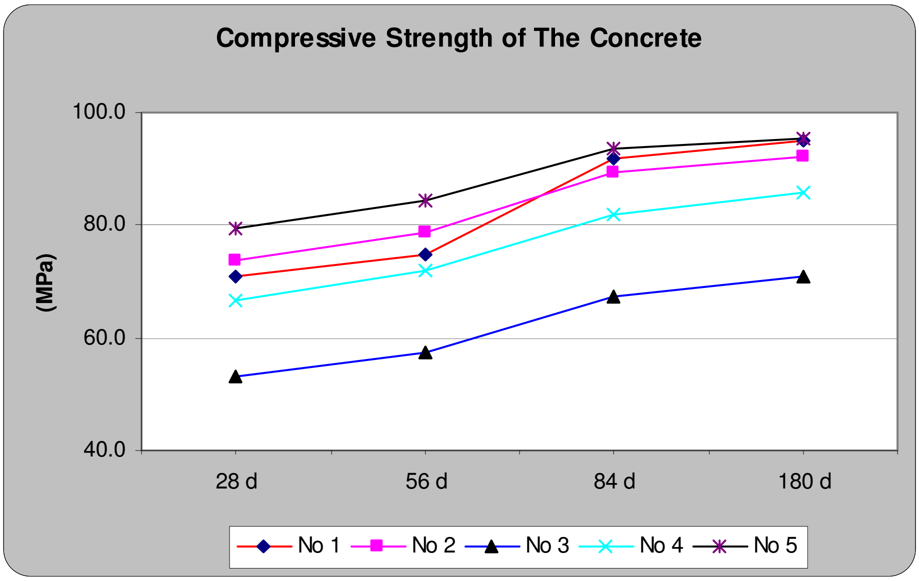


Figure 5.6: Compressive strength development of fly ash concrete

The Compressive strength development of high volume fly ash concrete shows all the mix proportions meet the strength requirement for high strength concrete (41 MPa), although the compressive strength did not meet the designed compressive strength of 80 MPa at 28 days. However, at 56 days the high volume ultra fine fly ash concrete using lime water as mixing water and using basalt fibre as strengthening material nearly has the same compressive strength as mix proportion design strength. After 84 days and beyond only high volume raw fly ash using tap water as mixing water which did not achieve compressive strength design of 80 MPa as achieved by the other mix proportions. The slow strength development confirms that the use of high volume fly ash as cement replacement reduces the compressive strength of fly ash in comparison to that in OPC especially in early ages as reported by other researchers (Ryan et al., 2007, Mehta, 2004, Mehta, 1985, Naik et al., 1998). The slow compressive strength development is possibly caused by the low cement used in high volume ultra fine fly ash, so that the concrete has low C_3A content from cement, the substance which mainly contributes for early age strength.

The graph (**Figure 5.6**) shows the increase of compressive strength with the increase of testing age for all mix proportions. Even if the water curing of the concrete is only up to 56 days, the hydration process still continues to achieve higher strength over longer period. The increase of compressive strength for high volume fly ash concrete in relation to the increase of testing age was similar to the observation of other researches (Hansen, 1990, Sivasundaram et al., 1990). Sivasundaram et al. (1990) also mentioned that the hydration process of fly ash concrete can continue up to 3.5 years due to its pozzolanic activity.

Nevertheless, after the testing age of 84 days, high volume fly ash concrete shows lower increase of compressive strength in comparison to the increase of strength before that period. Moreover, the slower rate of compressive strength development after 84 days might be caused by the decrease of pozzolanic material content after intensive reaction at early ages (Sivasundaram et al., 1990).

In addition, all of the mix proportions of high volume fly ash concrete have lower compressive strength in comparison to OPC concrete for all testing ages. However the high volume ultra fine fly ash concrete using tap water as mixing water has similar strength to OPC concrete which was achieved after 180 days of test.

5.3.2. Effect of material used in compressive strength of concrete.

There are three factors in mix proportioning of concrete which need to be analysed in giving effect to the compressive strength of concrete which consists of two different levels for each factor (**Table 5.1**).

To understood the effect of type of fly ash used, kind of water used and the utilization of basalt fibre, the compressive strength result was analysed using main effect graph and size of effect in design of experiment. The size of effect is the difference between the average response at the low level and the average response at high level. As there are four testing ages in strength development of compressive strength, there are also 4 size of effect calculation. **Figure 5.8** and **Figure 5.9** show the main effect graph of compressive strength development concrete in the design experiment from Minitab.

Worksheet 1 ***

↓	C1	C2	C3	C4	C5-T	C6-T	C7-T	C8	C9
	StdOrder	RunOrder	CenterPt	Blocks	Fly ash	Water	Fiibre	Compressive strength at 28 days	
1	4	1	1	1	UFFA	Lime water	Basalt fibre	73.78	
2	2	2	1	1	UFFA	Tap water	No fibre	70.90	
3	3	3	1	1	Raw	Lime water	No fibre	66.69	
4	1	4	1	1	Raw	Tap water	Basalt fibre	52.97	
5									

Figure 5.7: Input data of compressive strength at 28 days in Minitab worksheet

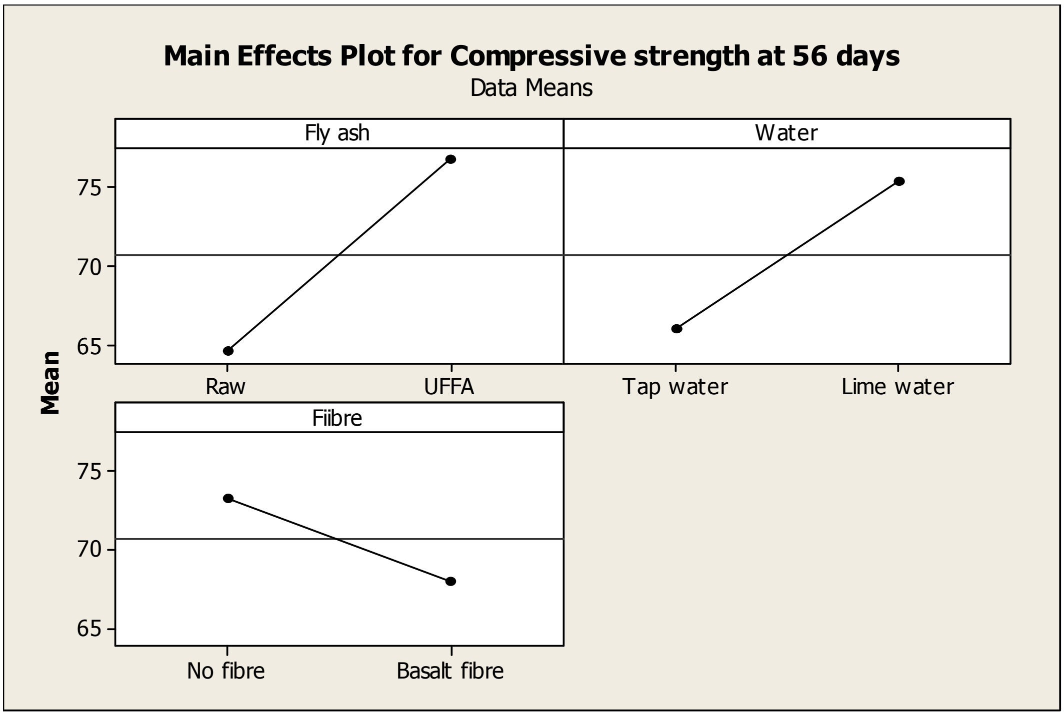


Figure 5.8: Main effect of compressive strength at 56 days

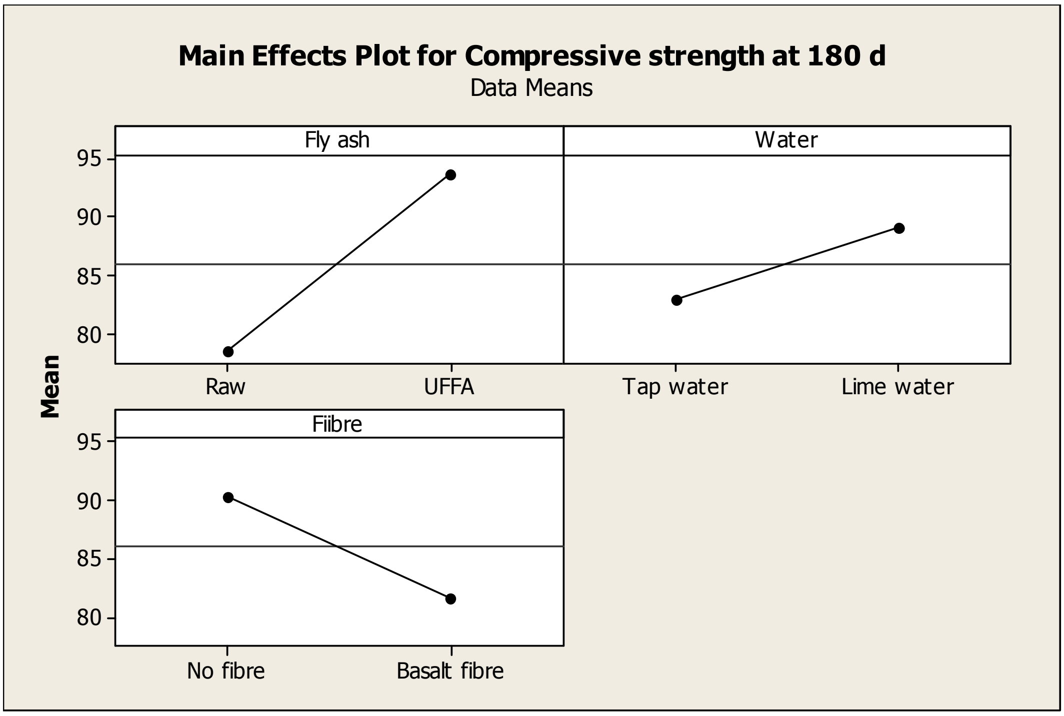
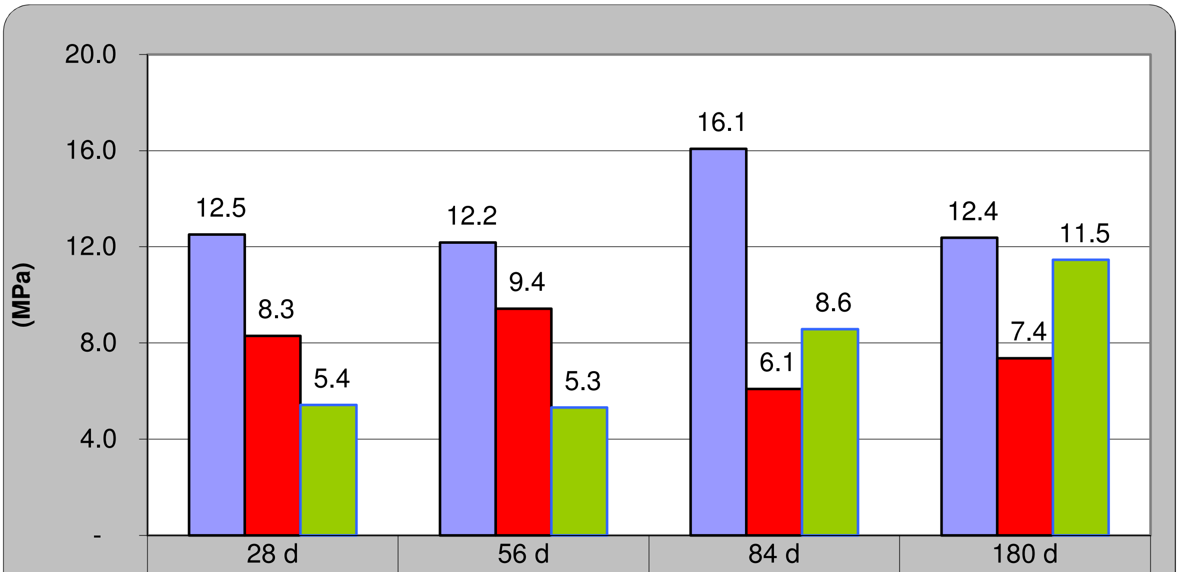


Figure 5.9: Main effect of compressive strength at 180 days

From the main effect graph, the size of effect can be calculated and the result is clearly presented in **Figure 5.10.**



	28 d	56 d	84 d	180 d
fly ash	12.5	12.2	16.1	12.4
water	8.3	9.4	6.1	7.4
Fibre	5.4	5.3	8.6	11.5

Figure 5.10: Compressive strength development Size of effect of fly ash, water, and basalt fibre for HVFA concrete

The graph (**Figure 5.10**) shows type of fly ash always becomes the most influencing factor in compressive strength of concrete as the size of effect is the highest in comparison to the other two factors for all of the testing ages. In this experiment, the use of ultra fine fly ash is the most significance in increasing the compressive strength. Furthermore, the kind of mixing water used and basalt fibre gave less contribution in compressive strength of concrete than the type of fly ash.

At the age of 28 days and 56 days the size of effect of kind of mixing water is higher than that of size of effect of basalt fibre, however; the size of effect type of water becomes less than the size effect of fibre at the ages of 84 days and 180 days. At the age of 28 days and 56 days the use of lime water as mixing water gave more contribution in increasing compressive strength of concrete in comparison to the presence or absence of basalt fibre. Nevertheless, at the age of 84 days and 180 days, the absence of basalt fibre was more important in increasing compressive strength of concrete than the use of lime water as mixing water.

The ultra fine fly ash gave significant influence in compressive strength of concrete because the small particle size of fly ash increases pozzolanic reaction with the $Ca(OH)_2$ to produce C-S-H substances. Hence, more C-S-H substances produced leads to better compressive strength. In addition the use of lime water as mixing water also increased the compressive strength of concrete in comparison to the concrete with tap water as mixing water as it increased the alkaline liquid in the concrete to increase pozzolanic reaction in concrete.

In addition, the use of basalt fibre gave contribution to the compressive strength of concrete only for the initial period (at 28 and 56 days). However, after longer period (84 days and beyond) the presence of basalt fibre reduced the compressive strength of concrete. The decrease of compressive strength might be caused by the volumetric loss of basalt fibre and the loss of strength of basalt fibre after being exposed in alkali environment (Sim et al., 2005). The previous experiment in Chapter 3 (**Figure 3.8**) also confirmed that basalt fibre lost its weight gradually when exposed continuously to alkali liquid. In this case, the alkali environment is the cement matrix which has pH between 12.5 – 13.5 (Mehta and Monteiro, 2006).

5.3.3. Modulus of rupture development of concrete

The test for modulus of rupture development of high strength concrete was carried out at the concrete ages of 28 days, 56 days, 84 days, and 180 days. The tests were conducted based on Australian standard for modulus of rupture on prismatic specimens of 100 x 100 x 350 mm (AS 1012.11, 2000). Also, the setup of the tests followed four point bending test or third-point loading test and the load was applied using hydraulic MTS testing machine with loading rate of 3.8 kN/minute until the maximum load is reached.

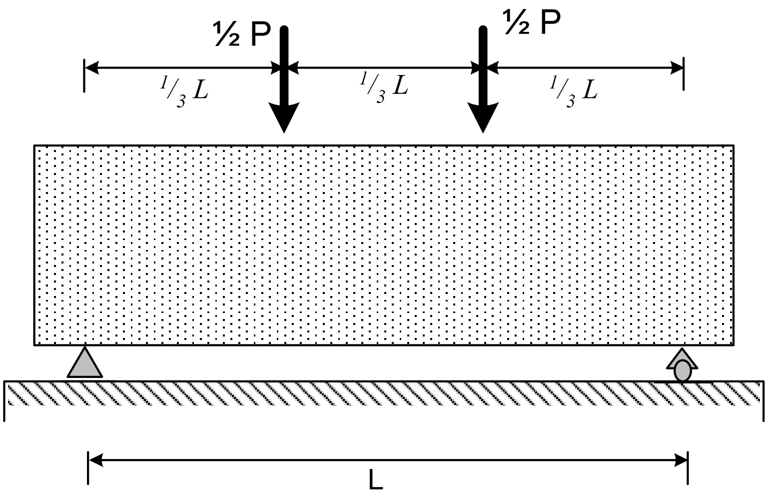


Figure 5.11: Four point bending test (Third-point loading) test set up

The modulus of rupture for concrete prismatic specimen of 100 x 100 x 350 mm which is tested with the testing setup as can be seen in **Figure 5.11** was calculated using following equation:

$$\boldsymbol{f_{ct}} = \frac{\boldsymbol{PL(1,000)}}{\boldsymbol{BD^2}}$$

where

f_{ct} = modulus of rupture (MPa)

P = maximum applied force indicated by the testing machine (kN).

L = span length (mm).

B = average width of the specimen at the section of failure (mm).

D = average depth of specimen at the section of failure (mm).

The development of modulus of rupture of high volume fly ash concrete incorporated with basalt fibre is shown in **Table 5.7** and **Figure 5.12**. Besides, modulus of rupture of OPC concrete is also presented as control mix proportion.

Table 5.7: Modulus of rupture development high volume fly ash concrete

	Modulus of rupture (MPa)			
	28 d	**56 d**	**84 d**	**180 d**
UFFA without basalt fiber, tap water (No 1)	6.50	6.81	7.66	9.05
UFFA with basalt fiber, lime water (No 2)	7.01	7.13	7.57	8.82
Raw Fly Ash with basalt fibre, tap water (No 3)	5.90	5.99	6.19	6.53
Raw Fly Ash without basalt fibre, lime water (No 4)	5.23	5.33	6.44	6.89
OPC without fibre, tap water (No 5)	7.21	7.54	8.21	9.63

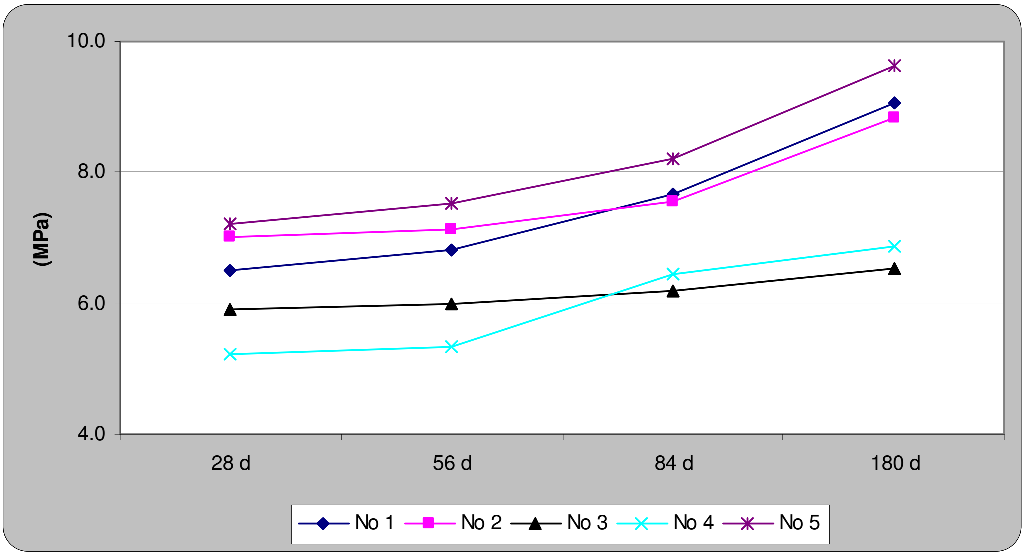


Figure 5.12: Modulus of rupture development of concrete

The graph in **Figure 5.12** shows the modulus of rupture of all the concrete mix proportions increases along with the increase of the concrete age. Although the water curing of high volume fly ash concrete was carried out only up to 56 days, the cement hydration to increase modulus of rupture was still continued without water curing which is same trend as compressive strength development of concrete. The increase of modulus of rupture for high volume raw fly ash concrete from 28 days to 180 days is around 20.6%, nevertheless; high volume ultra fine fly ash concrete and OPC concrete have modulus of rupture developments of 32.3% and 33.6% respectively.

As can be seen on the graph (**Figure 5.12**), high volume raw fly ash concrete has lower modulus of rupture development in comparison to high volume ultra fine fly ash concrete and OPC concrete. The lower modulus of rupture for raw fly ash in comparison to fine fly ash and OPC concrete was also reported by Duran-Herrera et al. (2011).

Furthermore, although the high volume ultra fine fly ash concrete has higher modulus of rupture than high volume raw fly ash concrete, its strength is still lower than that of OPC concrete. It is only at early ages that the modulus of rupture of high volume ultra fine fly ash concrete with basalt fibre has similar strength as that in OPC concrete. The lower modulus of rupture of coarse fly ash concrete in comparison to fine fly ash concrete or OPC concrete was also reported by Hazaree et al. (2006).

At early ages (28 days and 56 days) the modulus of rupture of high volume fly ash concrete with basalt fibre (No 2 and No 3) is slightly higher than the high volume fly ash concrete without basalt fibre (No 1 and No 4). It shows the contribution of basalt fibre in increasing concrete's modulus of rupture. As reported by many researchers, the use of fibre will significantly increase concrete's flexural properties (Kayali et al., 2003, Zollo, 1997).

Despite having higher modulus of rupture at early ages for basalt fibre concrete, its modulus of rupture at 84 days and 180 days is lower in comparison to the high volume fly ash concrete without basalt fibre. The decrease of modulus of rupture for longer periods might be caused by the brittleness of basalt fibre after exposure to alkali environment, i.e. cement paste. The decrease of modulus of rupture after longer periods is also confirmed by compressive strength development, which shows that the presence of basalt fibre after longer periods decreases the compressive strength.

Moreover, the modulus of rupture for all of mix proportion of high volume fly ash concretes are less than the modulus of rupture of OPC concrete for all testing ages.

5.3.4. Effect of material use in modulus of rupture

To analyse the effect of type of fly ash used, kind of water used and the use of basalt fibre in modulus of rupture of concrete, the modulus of rupture result was analysed using main effect graph and size of effect in design of experiment analysis. The size of effect was calculated at four different testing ages of modulus of rupture. **Figure 5.14.** and **Figure 5.15.**, show the main effect graph of modulus of rupture development concrete in the design experiment from Minitab.

Worksheet 1 ***

↓	C1	C2	C3	C4	C5-T	C6-T	C7-T	C8	C9
	StdOrder	RunOrder	CenterPt	Blocks	Fly ash	Water	Fibre	Modulus of rupture at 56d	
1	4	1	1	1	UFFA	Lime water	Basalt fibre	7.13	
2	2	2	1	1	UFFA	Tap water	No fibre	6.81	
3	3	3	1	1	Raw	Lime water	No fibre	5.33	
4	1	4	1	1	Raw	Tap water	Basalt fibre	5.99	
5									

Figure 5.13: Input data or modulus of rupture at 56 days in Minitab worksheet

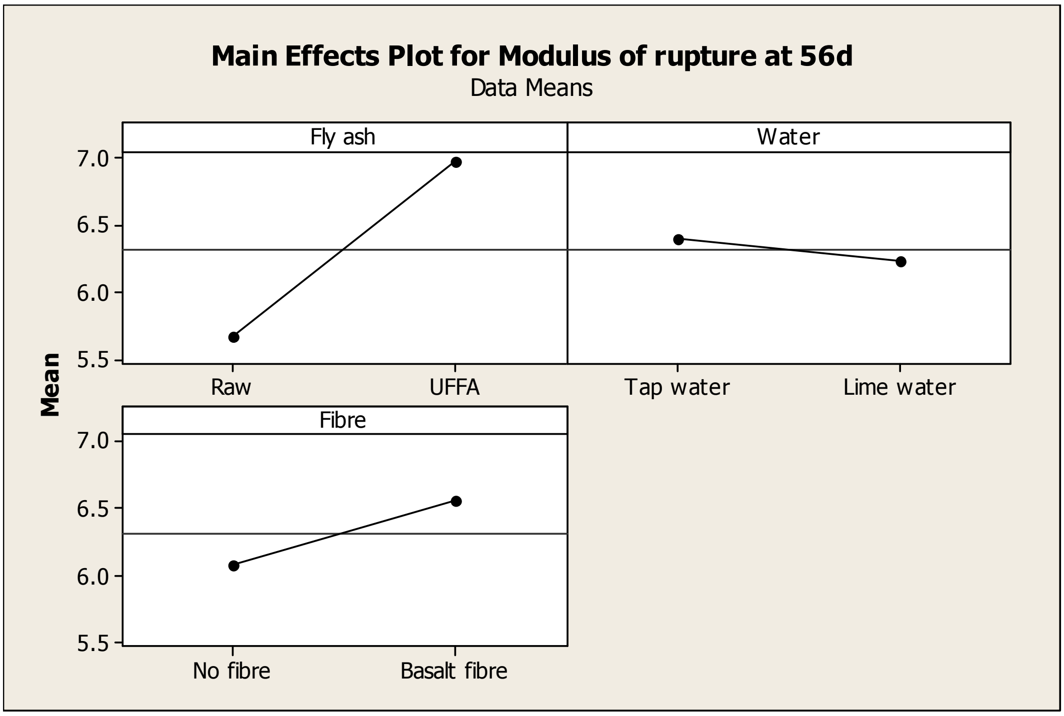


Figure 5.14: Main effect for modulus of rupture at 56 days

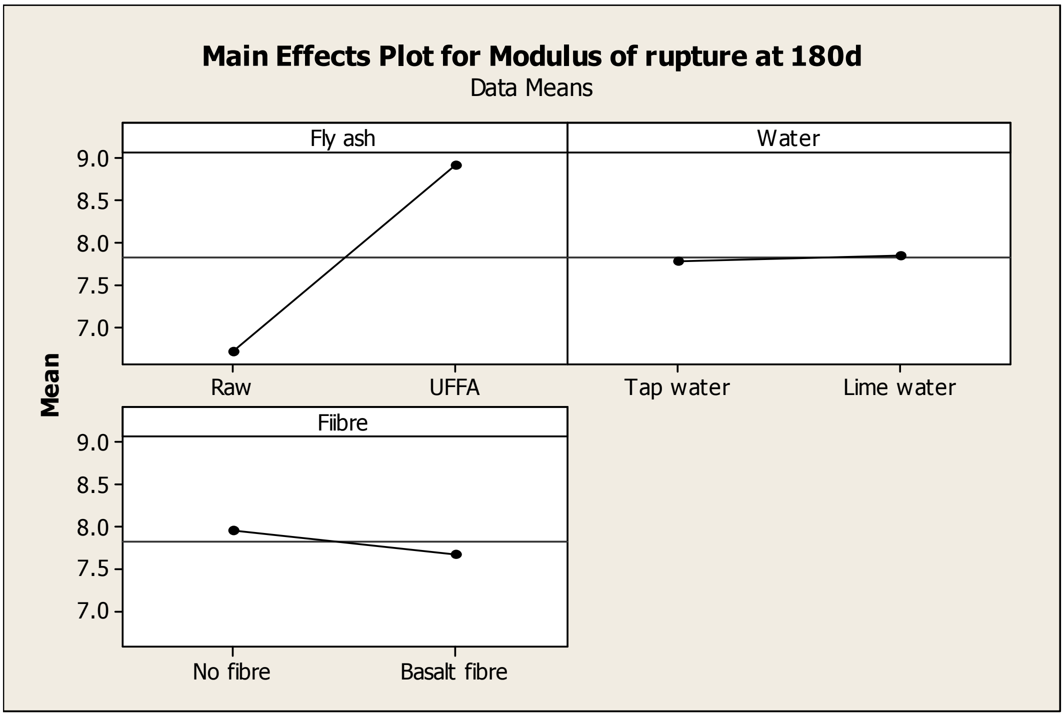
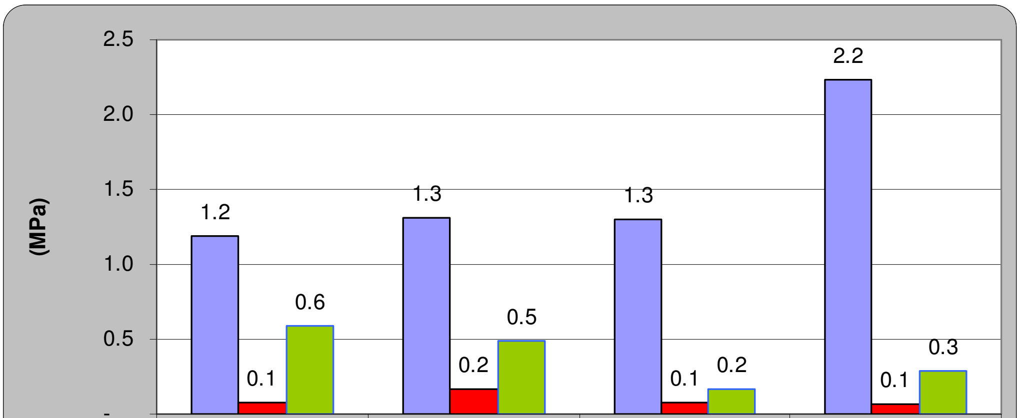


Figure 5.15: Main effect for modulus of rupture at 180 days



	28 d	56 d	84 d	180 d
fly ash	1.2	1.3	1.3	2.2
water	0.1	0.2	0.1	0.1
Fibre	0.6	0.5	0.2	0.3

Figure 5.16: Size of effect of fly ash, water, and fibre for modulus of rupture development HVFA concrete

The size of effect shows (**Figure 5.16**), the kind of fly ash is the most beneficial factor in increasing the modulus of rupture in comparison to the basalt fibre factor and the kind of mixing water for all testing ages. Regarding the kind of fly ash, the use of high volume ultra fine fly ash as cement replacement increases concrete's modulus of rupture in comparison to the use of high volume raw fly ash. Similar to the result of this study, the lower modulus of rupture for raw fly ash concrete in comparison to fine fly ash concrete was also reported by Hazaree et al. (2006).

The second important factor in giving contribution to modulus of rupture is the presence of basalt fibre. However, the contribution is related differently to the age of concrete as can be seen in main effect plot graph (**Figure 5.14 and Figure 5.15**). At early age, the presence of basalt fibre in high volume fly ash concrete contributes to increase modulus of rupture of concrete and the same result was also reported by previous researcher (Dias and Thaumaturgo, 2005). However, after 84 days and beyond, instead of increasing the modulus of rupture, the presence of basalt fibre decreases modulus of rupture. This phenomenon is possibly caused by the degradation of basalt fibre after exposure for longer period in alkali environment such as concrete. Rabinovich et al. (2011) also reported the same result of the degradation of basalt fibre after an exposure for longer period in alkali environment such as concrete especially when the diameter of basalt fibre is small. In addition, this trend is same as the compressive strength development.

Furthermore the kind of water gave no influence in the modulus of rupture of high volume fly ash concrete as can be seen in the small value of size of effect in comparison to the other two factors for all testing ages. Therefore, lime water contribution is negligible and makes the use of lime water or tap water has no effect in increasing or reducing concrete's modulus of rupture. In terms of concrete strength properties, the use of lime water only gives significant contribution to compressive strength but not to modulus of rupture.

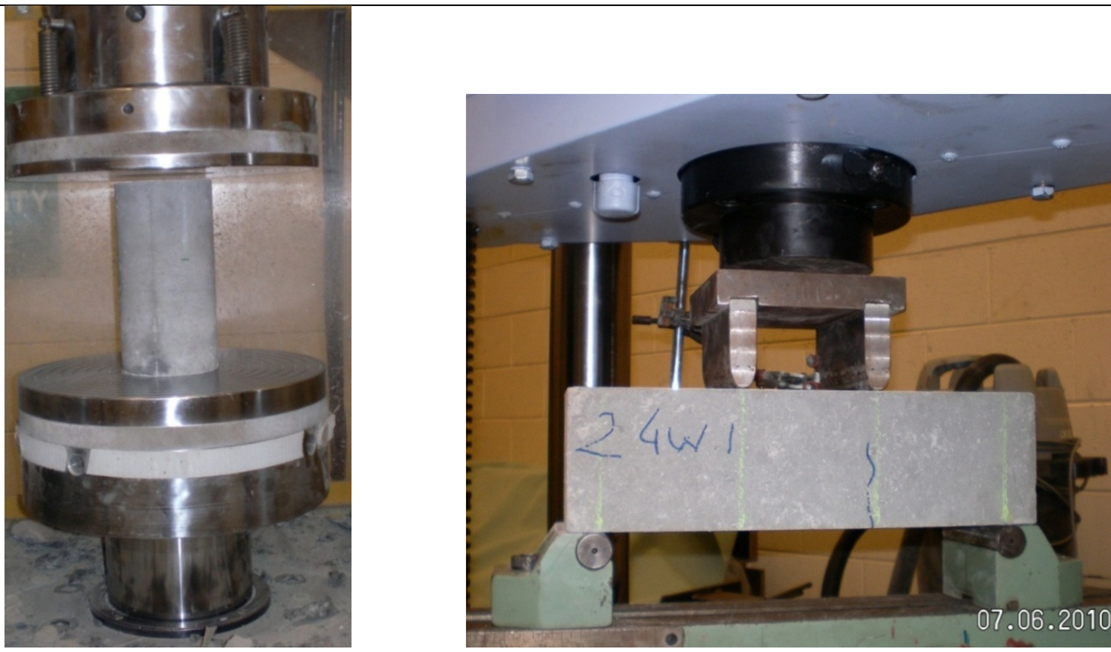


Figure 5.17: Compressive strength and modulus of rupture test

5.4. Confirmation on effect of basalt fibre in strength of concrete

The design of experiment in concrete strength analysis shows that the basalt fibre contributed to an increase in compressive strength and modulus of rupture of high volume fly ash concrete only at early ages but the high volume fly ash concrete lost its strength after longer period. Moreover, to confirm those strength results, additional investigation on effect of basalt fibre in concrete strength was also conducted. Hence, the effect of using basalt fibre on strength of concrete was analysed using the following mix proportions:

a) High volume ultra fine fly ash (UFFA) concrete with basalt fibre using lime water as mixing water (No 2).
b) High volume raw fly ash concrete with basalt fibre using tap water as mixing water (No 3).
c) High strength OPC concrete without fibre using tap water as mixing water (No 5).
d) High strength OPC concrete with basalt fibre using tap water as mixing water (No 6).
e) High strength OPC concrete with steel fibre using tap water as mixing water (No 7).

As can be seen in the list of mix proportion above, besides the mix proportion for high strength OPC concrete and high strength basalt fibre concrete, high strength OPC concrete using steel fibre as strengthening material was also prepared as a control mix.

5.4.1. Effect of basalt fibre on compressive strength of concrete

After conducting compressive strength test, the compressive strength development of high strength concrete was presented in the following **Table 5.8** and **Figure 5.18**.

Table 5.8: Compressive strength development of fibre concrete

	Compressive strength (MPa)			
	28 d	56 d	84 d	180 d
UFFA with basalt fiber, lime water (No 2)	73.78	78.84	89.45	92.25
Raw Fly Ash with basalt fibre, tap water (No 3)	52.97	57.23	67.28	71.06
OPC without fibre, tap water (No 5)	79.44	84.51	93.68	95.36
OPC with basalt fibre, tap water (No 6)	76.08	80.34	85.90	89.02
OPC with steel fibre, tap water (No 7)	83.24	87.07	96.12	99.11

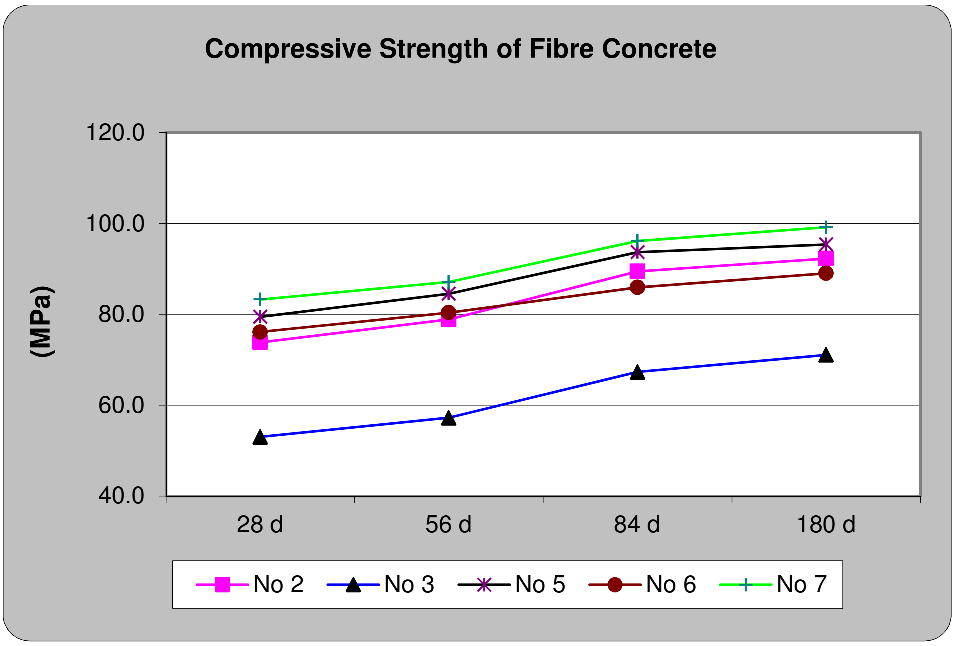


Figure 5.18: Compressive strength development of fibre concrete

The graph in **Figure 5.18** shows all of mix proportions meet the criteria as high strength concrete (minimum compressive strength of 41 MPa). In addition, the use of steel fibre slightly increased the compressive strength of high strength

OPC concrete as seen from the comparison of results from mix proportion No 5 and No 7. The compressive strength of steel fibre concrete is the highest compressive strength in comparison to all investigated mix proportions for all testing ages. The slightly increase of concrete's compressive strength with the use of steel fibre is also reported by previous researcher (Balendran et al., 2002, Chunxiang and Patnaikuni, 1999).

The graph in **Figure 5.18** also shows high volume ultra fine fly ash and high strength OPC concrete incorporated with basalt fibre has similar strength at early ages of test (No 2 and No 6). However, after longer period the OPC concrete has slightly lower compressive strength in comparison to high volume ultra fine fly ash. The higher compressive strength for high volume ultra fine fly ash is possibly caused by the presence of high volume silica in fly ash which binds $Ca(OH)_2$ from cement hydration process resulting in decrease of the alkalinity of cement paste. The decrease of alkalinity in high volume ultra fine fly ash concrete protects the basalt fibre from rapid loss of its volumetric stability in comparison to basalt fibre's rapid loss of volumetric stability in OPC concrete.

The ideal contribution of fibre in increasing compressive strength of concrete should follow from the steel fibre trend of strength development in high strength OPC concrete which is always similar to OPC concrete without fibre. However, the presence of basalt fibre in concrete, which slightly decreases compressive strength of OPC concrete and further decreases after longer period, was different from steel fibre concrete.

5.4.2. Effect of basalt fibre on concrete's modulus of rupture

To analyse the effect of basalt fibre on concrete's modulus of rupture, additional three mix proportions of high strength OPC concrete were cast and their modulus of rupture strength development are shown in **Table 5.9** and **Figure 5.19**.

Table 5.9: Modulus of rupture strength development of high strength concrete with fibre

	Modulus of rupture (MPa)			
	28 d	**56 d**	**84 d**	**180 d**
UFFA with basalt fiber, lime water (No 2)	7.01	7.13	7.57	8.82
Raw Fly Ash with basalt fibre, tap water (No 3)	5.90	5.99	6.19	6.53
OPC without fibre, tap water (No 5)	7.21	7.54	8.21	9.63
OPC with basalt fibre, tap water (No 6)	7.59	7.97	8.02	8.15
OPC with steel fibre, tap water (No 7)	9.39	10.77	10.84	12.65

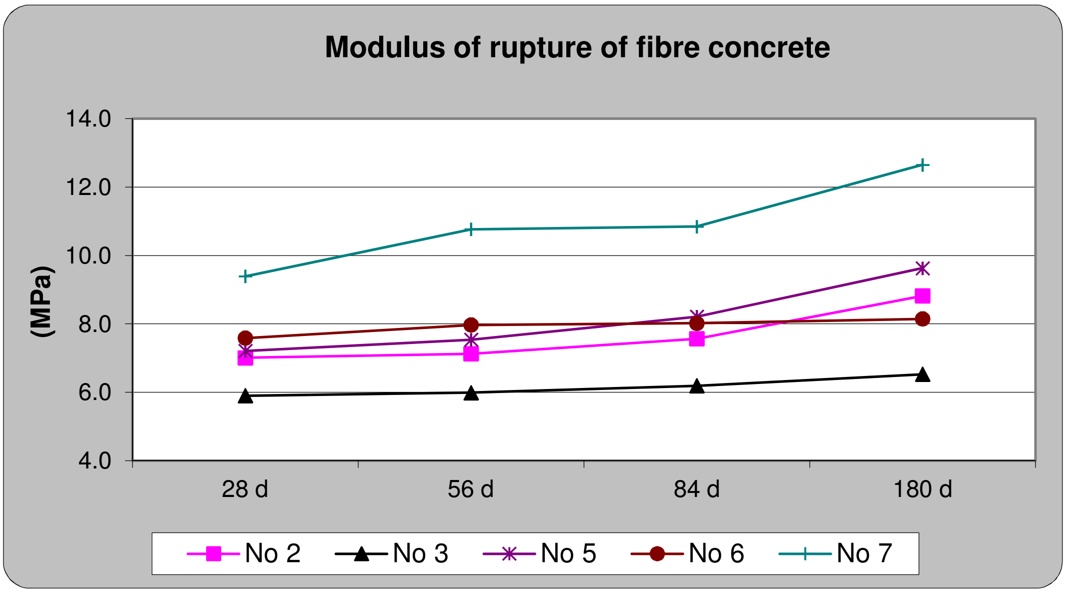


Figure 5.19: Modulus of rupture development of high strength concrete with fibre

The result of modulus of rupture shows that the basalt fibre does not give contribution in increasing concrete's modulus of rupture. The less contribution of basalt fibre can be seen by the relatively same modulus of rupture between high strength OPC concrete and high strength OPC concrete with basalt fibre (Mix proportion No 5 and No 6). In addition, the modulus of rupture of OPC concrete is similar to modulus of rupture of high volume ultra fine fly ash concrete with basalt fibre. Moreover, the less contribution of basalt fibre can be seen by the lower modulus of rupture for OPC concrete using basalt fibre in comparison to OPC concrete without fibre after longer period of testing.

The least contribution of basalt fibre in increasing modulus of rupture is possibly caused by the brittleness of basalt fibre after exposure to alkali environment such as cement paste. Previous experiment in sub **Chapter 3.2.4** confirms the degradation of basalt volume after being immersed in alkali solution.

In regard to the contribution of fibre in increasing modulus of rupture, the significant contribution of fibre can be seen by the use of steel fibre in high strength OPC concrete which increase modulus of rupture around 30% for all of testing ages. The significant contribution of steel fibre in increasing modulus of rupture was also reported by previous researchers (Balendran et al., 2002, Yew et al., 2011)

Figure 5.20: The fracture of basalt fibre concrete beam after testing

Figure 5.21: Steel fibre concrete beam after testing

The least contribution of basalt fibre in increasing modulus of rupture can also be confirmed by the observation on concrete specimen after test. When concrete beam achieved maximum load, the beam with basalt fibre was totally cut off, however; the steel fibre beam remained on their shape even though it had large deflection and crack (**Figure 5.20** and **Figure 5.21**). Moreover, the least contribution of basalt fibre in modulus of rupture is also demonstrated by the observed fractures in which it was easy to find some steel fibres that still remained in concrete (**Figure 5.22**). Whereas on fracture surface of basalt fibre beam, there is no basalt fibre trace due to the brittleness of basalt fibre as if there is no basalt fibre added at all (**Figure 5.23**).

Figure 5.22: Some steel fibre on the fractured surface of steel fibre concrete

Figure 5.23: No trace of basalt fibre on fractured surface of basalt fibre concrete

Those experiments confirm that basalt fibre is not appropriate as strengthening material for flexure in concrete. In addition to the result, to reduce the brittleness of basalt fibre in cement paste, further treatment needs to be applied to increase the stabilization of basalt fibre in concrete.

5.5. Mix proportion for optimum compressive strength

5.5.1. Compressive strength

Based on the result of main factor and size of effect analyses of compressive strength in design experiment, it is found that kind of fly ash is the most significant factor giving contribution to the strength of concrete in which the use of ultra fine fly ash (UFFA) gives significant improvement in the compressive strength in comparison to the use raw fly ash. After the type of fly ash used, the kind of mixing water becomes the second factor giving contribution to compressive strength with the beneficial use of lime water in increasing compressive strength compared to the use of tap water. Moreover, in regard to the use of basalt fibre in concrete, the absence of basalt fibre is useful in increasing compressive strength of concrete.

Hence, from the analysis of observed factors used in this experiment, it can be concluded that to produce highest compressive strength of concrete which considers those three factors, the most optimum combination for the mix proportion is by using high volume ultra fine fly ash, lime water as mixing water and without the use of basalt fibre.

From the conclusion of optimum mix proportion to produce highest compressive strength, the mix proportion of high volume ultra fine fly ash concrete with lime water was prepared. The mix proportion is same as the mix proportion

No 1, but the mixing water is lime water. In addition, similar to the previous test, the concrete specimens' curing was carried out until the day of test at 14 days, 28 days and 56 days. Moreover, the result of OPC concrete compressive strength as control mix proportion was also presented.

Table 5.10: Mix proportion for optimum strength and OPC concrete

Mix proportion	Cement	Fly ash	Water	Agregate		HRWR
				fine	Coarse	
	(kg/m3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(litre/m^3)
UFFA without basalt fiber, lime water (No 10)	225.0	225.0	141.0	835.0	994.0	7.0
OPC without fibre, tap water (No 5)	450.0	-	137.0	912.0	994.0	13.9

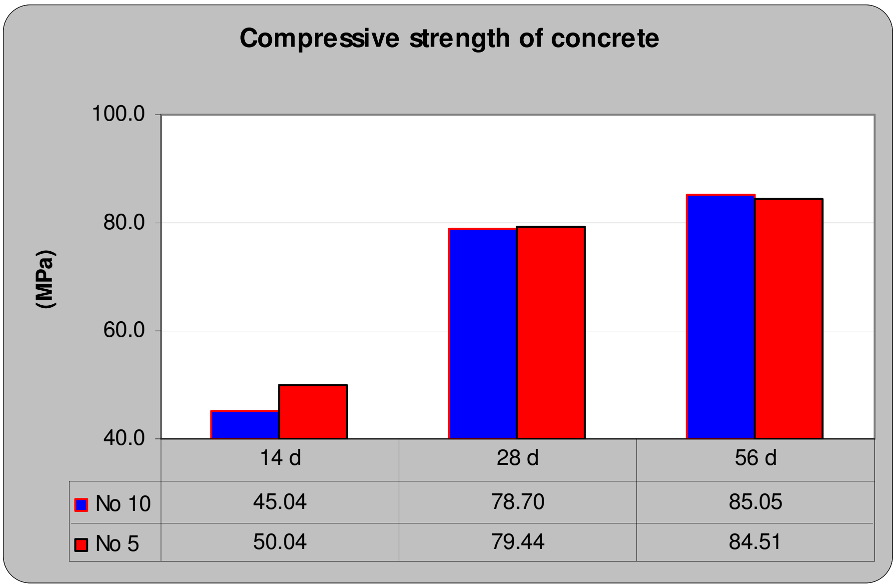


Figure 5.24: Compressive strength development of optimum mix proportion and OPC concrete

Figure 5.24 shows the compressive strength development of high volume ultra fine fly ash concrete with lime water and compressive strength of high strength OPC concrete. Both of the mix proportions satisfy the mix design of 80 MPa at 28 days. Additionally, the high volume ultra fine fly ash concrete with lime water has comparable strength development as high strength normal concrete starting from 28 days and beyond regardless of the amount of ultra fine fly ash used which is up to 50% as cement replacement. This result is noteworthy as previous research using high volume fine fly ash reduced the compressive strength of concrete at the testing age of 56 days by 15% to 19.0% in comparison to the OPC concrete (Sengul et al., 2005, Sengul and Tasdemir, 2009).

Moreover, it proves that the use of lime water in high volume ultra fine fly ash concrete produces better reaction with silica in ultra fine fly ash in comparison to the use of hydrated lime (in the form of powder) to give same compressive strength as normal concrete. Similar research also examined the utilization of hydrated lime in increasing compressive strength of high volume fly ash concrete in comparison to high volume fly ash without hydrated lime. However, the compressive strength in that research was not compared to compressive strength of OPC concrete (Barbhuiya et al., 2009).

5.5.2. Modulus of elasticity

After finding the optimum mix proportion in producing high strength high volume ultra fine fly ash concrete, further experiments and analysis were conducted for all of eight mix proportions, i.e.:

a) High volume ultra fine fly ash (UFFA) concrete without basalt fibre using lime water as mixing water (No 10).
b) High volume ultra fine fly ash (UFFA) concrete without basalt fibre using tap water as mixing water (No 1).
c) High volume ultra fine fly ash (UFFA) concrete with basalt fibre using lime water as mixing water (No 2).
d) High volume raw fly ash concrete with basalt fibre using tap water as mixing water (No 3)

e) High volume raw fly ash concrete without basalt fibre using lime water as mixing water (No 4)

f) High strength OPC concrete without fibre using tap water as mixing water (No 5)

g) High strength OPC concrete with basalt fibre using tap water as mixing water (No 6)

h) High strength OPC concrete with steel fibre using tap water as mixing water (No 7)

This section will discuss further experiment in mechanical properties of concrete i.e. modulus of elasticity test. In addition, durability tests and microstructure analysis of concrete were presented in **Chapter 6**.

The modulus of elasticity of concrete was tested at the curing age of 56 days using MTS compression testing machine to apply the load. Based on Australian standard (AS 1012.17, 1997), the loading rate of 15 ± 2 MPa was applied up to 40% of average compressive strength. To record the deformation of specimens during the test, a pair of LVDTs was installed on the opposite side of concrete cylinder. Therefore, the load and deformation data can be recorded every second.

Figure 5.25: modulus of elasticity test

The modulus of elasticity for material under tension or compression is calculated from the slope of stress-strain curve of cylinder of concrete under uniaxial loading. The result of modulus of elasticity for all of the concrete in this experiment is shown in **Figure 5.26**. The correlation between the modulus of elasticity of concrete and its compressive strength (f_c') based on ACI 363R is also presented as comparison. The modulus of elasticity for high strength concrete based on compressive strength can be calculated using following equation (ACI 363R-92., 1997) :

$E_C = 3{,}320\ \sqrt{f_c'} + 6{,}900$ MPa

for 21 MPa < f_c' < 83 MPa

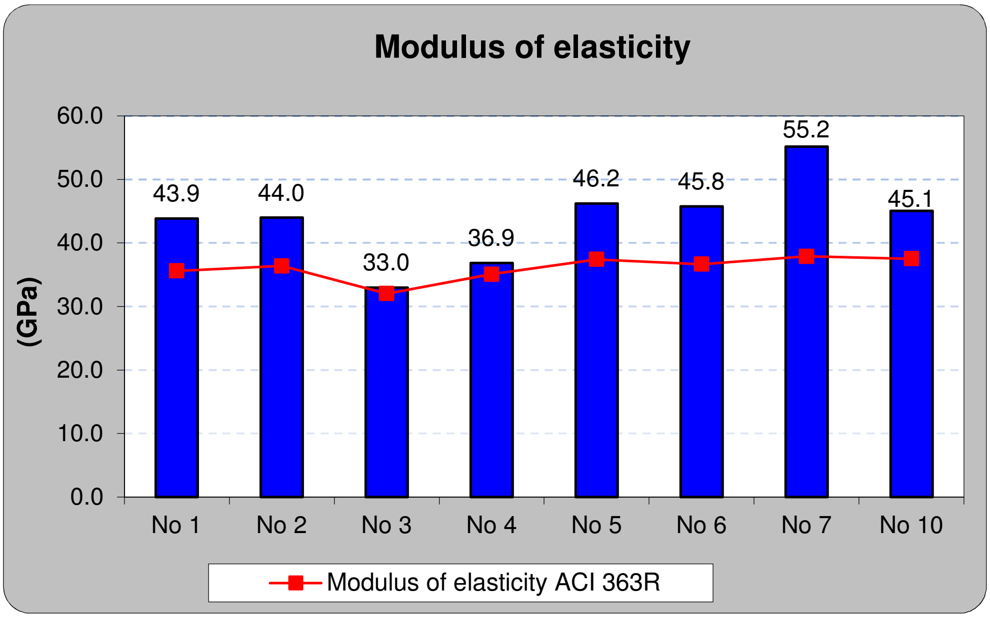


Figure 5.26: Modulus of elasticity of high strength concrete

Based on the graph (**Figure 5.26**), modulus of elasticity of all the concretes satisfy the compressive strength and modulus of elasticity correlation for high strength concrete from ACI 363R and even higher for some mix proportions. The correlation shows that higher the compressive strength of the concrete the higher of the modulus elasticity.

In addition, high volume raw fly ash concretes (No 3 and No 4) have the lowest modulus of elasticity out of all the mix proportions, and this result is same as the formula of correlation between compressive strength and modulus elasticity (ACI 363R-92., 1997). The lower modulus of elasticity for high volume raw fly ash concrete in comparison to high volume fine fly ash concrete and OPC concrete was also reported by Bouzouba et al. (2001) .

Regarding to the use of fibre in concrete, there is no influence of the utilization basalt fibre in increasing modulus of elasticity of concrete. This result is possibly caused by the brittleness of basalt fibre as reported in compressive strength test and modulus of rupture test of basalt fibre concrete. Previous research also reported about no-contribution of basalt fibre in static modulus (Ramakrishnan et al., 1998). Furthermore, the use of steel fibre as concrete strengthening material increases the modulus of elasticity as it gives the highest modulus of elasticity in comparison to all of mix proportions prepared, and this result is in line with the former studies (Ibrahim and Bakar, 2011, Khaloo and Afshari, 2005).

5.6. Summary of chapter 5

The investigation on the effect of type of fly ash, kind of mixing water and the utilization of basalt fibre on the strength of concrete can be summed up as follow:

1) The use of ultra fine fly ash is the most significant factor in increasing strength development of concrete, both in compressive strength and modulus of rupture.
2) Lime water becomes the second important factor to increase concrete compressive strength development; however it has no effect on concrete's modulus of rupture.
3) Lime water gives significant effect in increasing compressive strength development of high volume ultra fine fly ash to be similar to OPC concrete started at the testing age of 28 days. Nevertheless, different from the compressive strength development, it is found that the modulus of rupture development of high volume ultra fly ash concrete is lower than that of OPC concrete.
4) The contribution of basalt fibre to increase modulus of rupture of concrete is only found at early ages, however; after longer period the modulus of rupture in

concrete using basalt fibre is lower than OPC concrete without fibre. The lower modulus of rupture after longer period of testing is due to the lower volumetric stability of basalt fibre in alkali environment.

As mentioned earlier, high performance concrete not only depends on its mechanical properties but also on its durability. Therefore, the next chapter will discuss the durability properties of high volume fly ash concrete focusing on the optimum mix proportion made of a combination of the use of high volume ultra fine fly ash, lime water as mixing water and the absence of basalt fibre.

6. Durability test and microstructure analysis of High performance concrete with high volume ultra fine fly ash reinforced with Basalt fibre

6.1. Overview

The previous chapter shows high strength concrete can be produced using high volume ultra fine fly ash as cement replacement. It was found that, the optimum mix proportion to produce highest compressive strength considering three factors (type of fly ash, kind of mixing water and utilization of basalt fibre) is the mix proportion with the combination of using high volume ultra fine fly ash, lime water as mixing water without the use of basalt fibre.

The high strength concrete mix proportion was specially made of selected pozzolanic materials and employed chemical admixture as requirement in high strength concrete mix proportion (ACI 363R-92., 1997). Also, the utilization of a low water/cement ratio is essentially considered. By using the special mix proportion, the concrete has not only high strength, but also significant low permeability as a main factor of durable concrete produced (Khalil, 2002). Hence, in this chapter, the investigation on the durability of the high strength concrete is presented.

The durable concrete is very important to maintain concrete in its original form, quality, and serviceability especially when exposed to aggressive environment (ACI 201.2R-01, 2001). Basically, there is no material which is naturally durable because the interaction of material's microstructure with environment consequently changes the properties of the materials. Hence, concrete needs sufficient curing to have adequate resistance before it is exposed to aggressive environment. Based on previous experiment on mortar compressive strength, the high volume ultra fine fly ash mortars needs 56 days for curing to have higher compressive strength than OPC mortar. For that reason, the durability test in this research was conducted after curing of the concrete specimen in water tank for 56 days.

The durability test of concrete was examined on the following eight mix proportions of concrete, i.e.

a) High volume ultra fine fly ash (UFFA) concrete without basalt fibre using tap water as mixing water (No 1).
b) High volume ultra fine fly ash (UFFA) concrete with basalt fibre using lime water as mixing water (No 2).
c) High volume raw fly ash concrete with basalt fibre using tap water as mixing water (No 3).
d) High volume raw fly ash concrete without basalt fibre using lime water as mixing water (No 4).
e) High strength OPC concrete without fibre using tap water as mixing water (No 5).
f) High strength OPC concrete with basalt fibre using tap water as mixing water (No 6).
g) High strength OPC concrete with steel fibre using tap water as mixing water (No 7).
h) High volume ultra fine fly ash (UFFA) concrete without basalt fibre using lime water as mixing water (No 10).

The durability test of the high strength concrete comprises water absorption test, carbonation test, sulfate resistance test and rapid chloride penetration test. Besides these durability tests, the microstructure analysis of concrete was also conducted.

6.2. Durability test of concrete

6.2.1. Water absorption test of concrete

Water absorption test was conducted to study moisture transport in concrete, a main property which give influence to the durability of concrete (Kim et al., 2012). The test was conducted based on Australian Standard, determination of water absorption and apparent volume of permeable voids in hardened concrete (AS 1012.21., 1999). There are two kinds of absorption tested, i.e. immersed water absorption and saturated water absorption. In addition, the apparent volume of permeable voids (AVPV) was also determined.

Immersed absorption measures the total water that can be absorbed by the concrete after soaking the specimens in water for two days while saturated absorption measures the total absorption of water when the specimen is in saturated state. In saturating the specimens, the method of preparing a concrete specimen for rapid chloride penetration testing method in ASTM standard was used (ASTM C 1202 -97., 2002). By using this method, the sample was vacuumed for three hours to suck up all the entrapped air in concrete voids before soaking it into water for 18 hours. In addition, AVPV estimates the volume of permeable pore space in hardened concrete and becomes an accepted indicator of durability of concrete (CCAA Report, 2009, Fick, 2008).

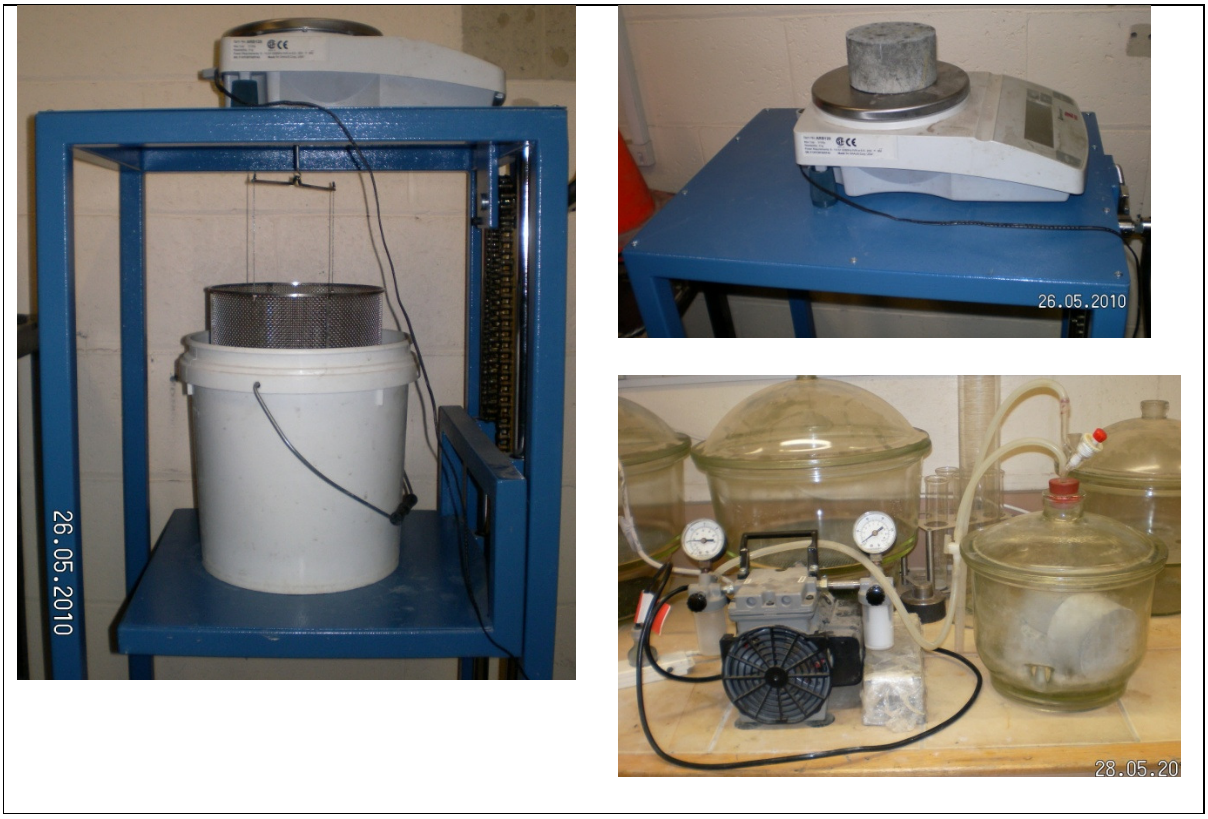


Figure 6.1: Absorption test of concrete

The test for water absorption of concrete was conducted after water curing at the age of 56 days and 180 days. The test was carried out for both testing ages to support the result of the other durability test experiments that were conducted at the age of 56 days and 180 days. The specimen for water absorption test was made by cutting a 100 mm diameter x 200 mm height concrete cylinder into 3 specimens.

Table 6.1: Water absorption of concrete

	(10)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Immersed absorption								
56 d	1.11%	1.57%	1.41%	2.08%	1.87%	2.53%	2.88%	2.38%
180 d	0.96%	1.28%	1.24%	1.88%	1.66%	2.11%	2.30%	2.13%
Saturated absorption								
56 d	1.36%	1.78%	1.69%	2.39%	2.19%	2.92%	3.28%	2.61%
180 d	1.18%	1.59%	1.30%	2.07%	1.73%	2.38%	2.46%	2.35%
Apparent volume of permeable voids								
56 d	3.36%	4.34%	4.05%	5.41%	5.10%	6.98%	7.58%	6.35%
180 d	2.84%	3.90%	3.44%	4.78%	4.21%	5.57%	5.96%	5.88%

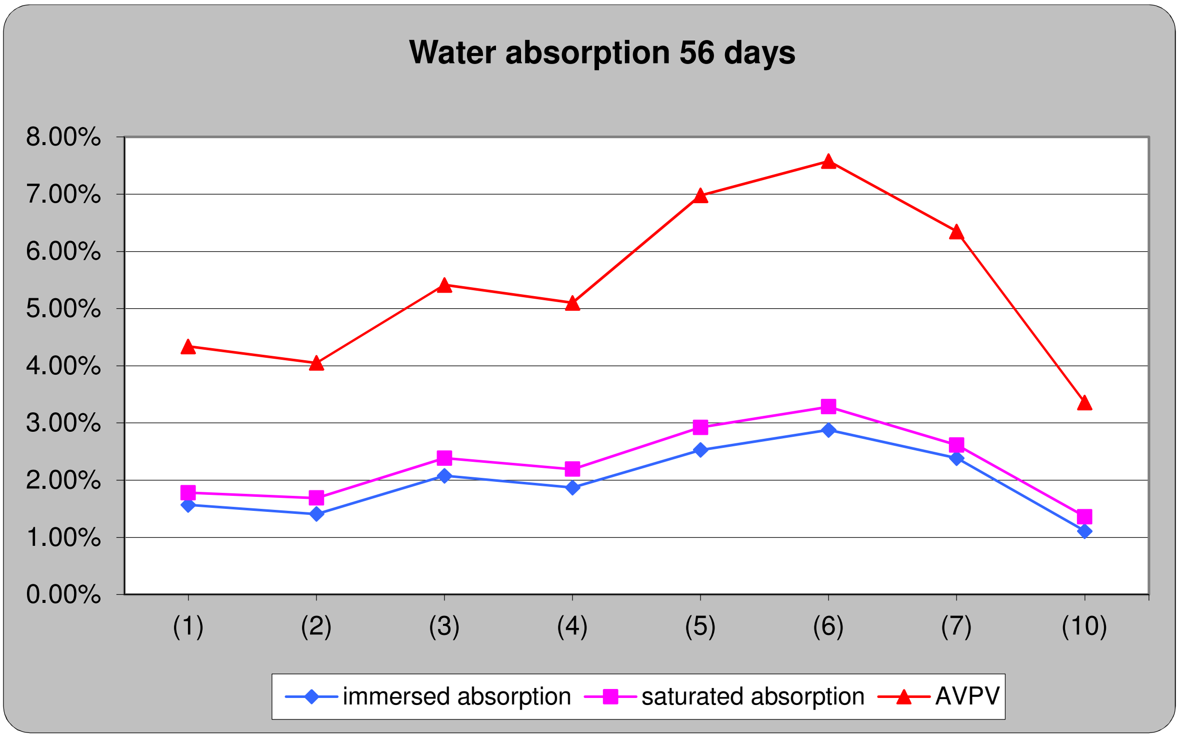


Figure 6.2: Water absorption at 56 days

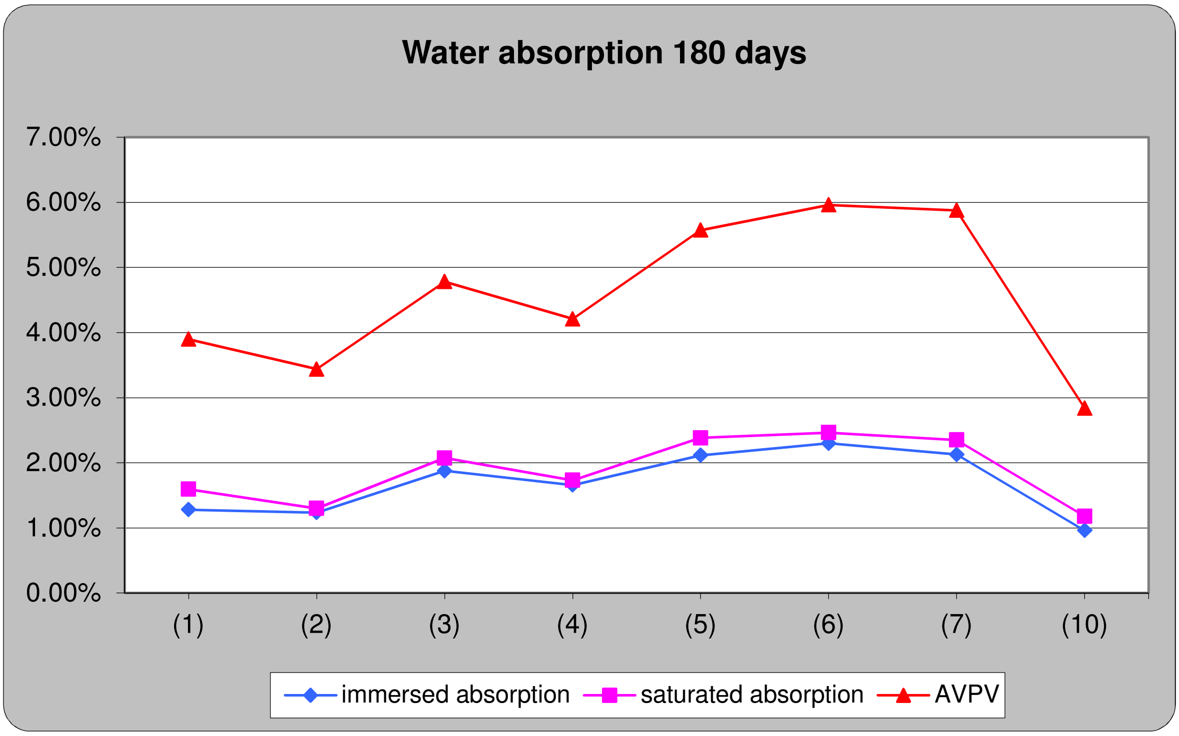


Figure 6.3: Water absorption at 180 days

The results of water absorption show the water absorption properties of concrete increase along with the increase of testing age. This result confirms previous result on strength development of concrete (**Chapter 5**) that hydration process of high strength concrete still continues after curing for 56 days even after the testing age of 180 days to increase concrete properties. In addition, the use of high volume fly ash produces lower immersed absorption, lower saturated absorption and lower apparent volume of permeable voids in comparison to OPC concrete. the lower water absorption properties of high volume fly ash concrete in comparison to OPC concrete were also elaborated by previous researcher (Crouch et al., 2007). Further decrease in water absorption properties can be seen by the use of ultra fine fly ash as well as by the use of lime water which slightly contributes in lowering water absorption properties of concrete. The permeability of the transition zone surrounding the aggregate as well as the permeability of the cement paste as investigated by Haque and Kayali (1998) is possibly one of the factors causing lower water absorption of fly ash concrete. Moreover, the discontinuation of pore structure of High volume fly ash concrete system also contributes to the lower water absorption (Malhotra and Mehta, 2005).

The less water absorption properties of high volume fly ash, particularly the lower apparent volume of permeable voids (AVPV), will result in better durability of concrete according to VicRoads guidance of concrete durability classification which related to AVPV value.

Table 6.2: VicRoads classification for concrete durability based on the AVPV (CCAA Report, 2009)

Durability classification indicator	**Vibrated cylinders** (AVPV %)	**Rodded cylinders** (AVPV %)	**Cores** (AVPV %)
6. Excellent	< 11	< 12	< 14
7. Good	11 – 13	12 – 14	14 – 16
8. Normal	13 – 14	14 – 15	16 – 17
9. Marginal	14 – 16	15 – 17	17 – 19
10. Bad	> 16	> 17	> 19

*

According to VicRoads classification under vibrated cylinders criteria, all the mix proportions in this study indicate excellent classification of concrete durability as the AVPV is below 11% for all mix proportions.

6.2.2. Carbonation

Carbonation is a result of reaction between $Ca(OH)_2$ in concrete and CO_2 from atmosphere. Carbonation test was conducted to investigate the reaction between carbon (CO_2) in atmosphere and concrete which makes degradation of concrete's pH which leads to depassivate steel reinforcement and causes corrosion to occur (Papadakis et al., 1989, RILEM CPC-18, 1984). Moreover, the carbonation test for this research was accelerated carbonation test which utilized a carbonation chamber to keep the specimen for testing. The carbonation chamber was maintained to have carbon concentration of 3.5%, relative humidity of 65%, and the temperature maintenance at 25^{o}C (Jones et al., 2000).

To supply the carbon gas into the chamber, a cylinder gas of CO_2 was prepared and an oxygen sensor was used to monitor the change of carbon concentration inside the chamber. Every time the oxygen increases as a result of the decrease of CO_2 concentration, some CO_2 was supplied inside the chamber to maintain CO_2 concentration of 3.5%.

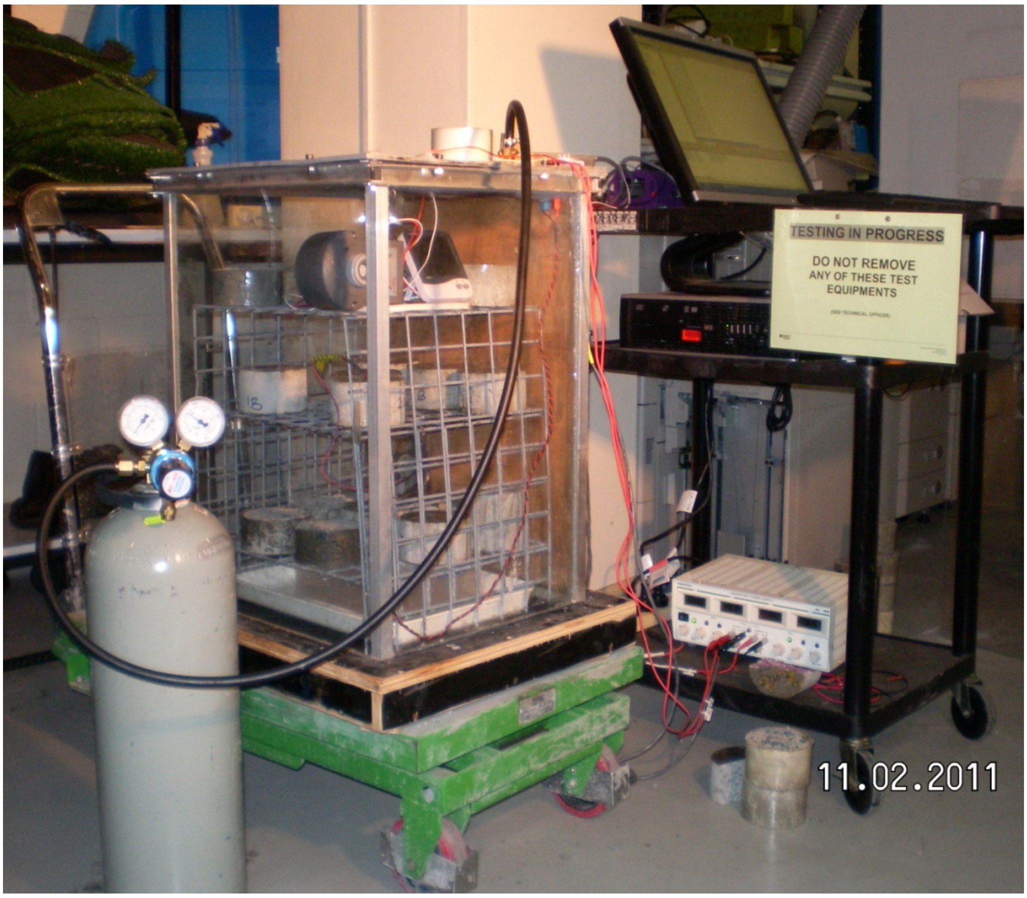
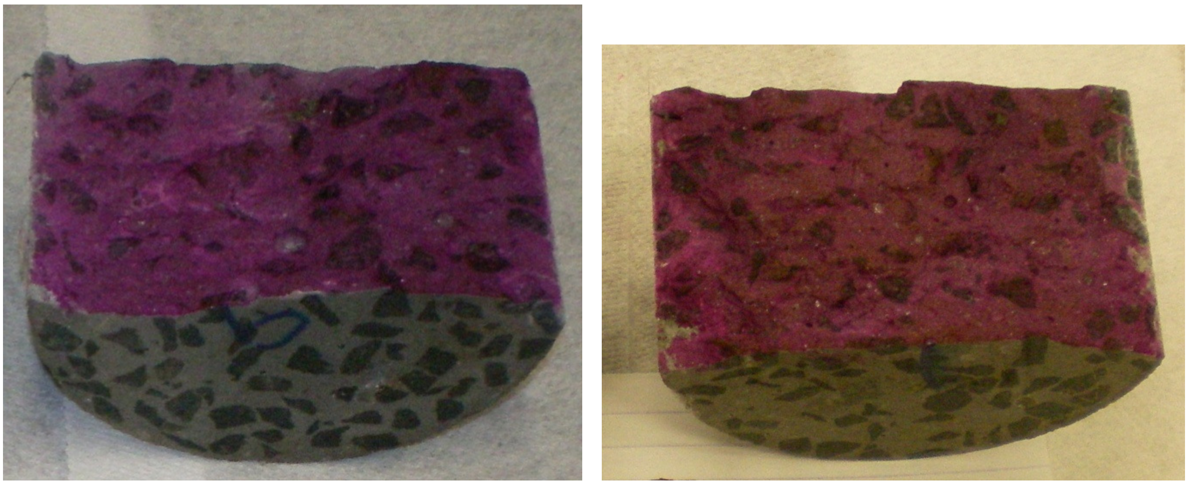


Figure 6.4: Setup carbonation chamber

Figure 6.5: Oxygen sensor, pH and temperature sensor

The specimens for this experiment has dimensions of 100 mm diameter and 60 mm height and ere cut from cylinder of diameter 100 mm x 200 mm height. Moreover, the top and bottom surfaces of specimens were sealed using epoxy resins to allow the carbonation only occurs through curved surface.

At the testing day of 7 days and 28 days, the specimens were taken out from the testing chamber and then cut into two pieces. Shortly after cutting the specimens, the pieces that have been cut were sprayed using phenolphthalein solution to check the depth of carbonation. The phenolphthalein would change the colour of un-carbonated concrete into purple and remain colourless for carbonated concrete. Therefore, the depth of carbonation can be measured using calliper. Some of carbonation concrete surface pictures at 7 days and 28 days are presented in **Figure 6.6 to Figure 6.10**.



(a) 7 days (b) 28 days

Figure 6.6: Depth of carbonation of concrete specimen no 10 at 7 and 28 days


(a) 7 days

(b) 28 days

Figure 6.7: Depth of carbonation of concrete specimen no 1 at at 7 and 28 days


(a) 7 days

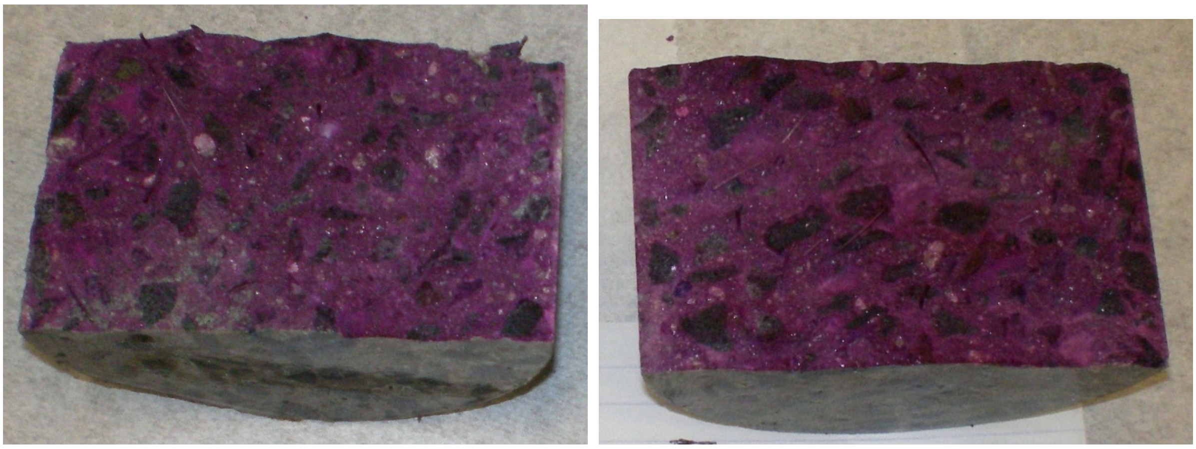
(b) 28 days

Figure 6.8: Depth of carbonation of concrete specimen no 3 at at 7 and 28 days


(a) 7 days

(b) 28 days

Figure 6.9: Depth of carbonation of concrete specimen no 6 at 7 and 28 days



(a) 7 days (b) 28 days

Figure 6.10: Depth of carbonation of concrete specimen no 7 at 7 and 28 days

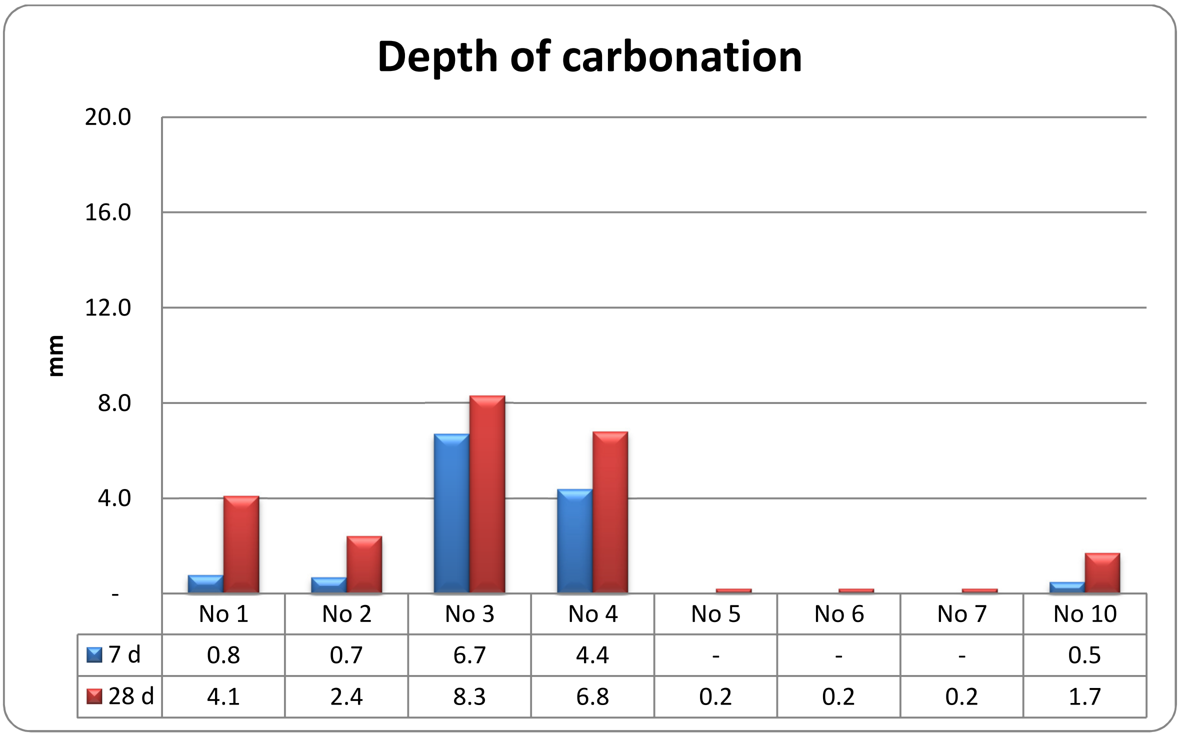


Figure 6.11: Depth of carbonation measurement at 7 and 28 days

The depth of carbonation measurement for all mix proportions (**Figure 6.11**) shows that the high volume fly ash concrete experiences higher carbonation attack from carbon dioxide in the atmosphere, and the carbonated region is deeper than OPC concrete. This deeper carbonation area of fly ash concrete is due to lower $Ca(OH)_2$ in fly ash concrete which resulted from pozzolanic reaction of fly ash concrete. With the same concentration of CO_2 in atmosphere, the lower $Ca(OH)_2$

results in high carbonation as less $Ca(OH)_2$ is available in concrete and it needs less CO_2 to neutralize the concrete leading to easier carbonation of fly ash concrete than that in OPC concrete (Burden, 2006, Quan, 2005). It is understandable that the use of lime water increases carbonation resistance of fly ash concrete as more $Ca(OH)_2$ is available in concrete, and it needs more CO_2 to neutralize the concrete.

Concerning the concrete carbonation resistance, the use of high volume ultra fine fly ash increases the concrete carbonation resistance in comparison to the use of high volume raw fly ash. The increase might have resulted from the decrease of permeable voids volume (AVPV) in concrete that makes concrete denser and offer better resistance to the ingression of CO_2. Similarly, Das and Pandey (2011) have examined the increase of carbonation resistance which is caused by the increase of fly ash fineness.

In addition, the longer the concrete is exposed to carbon dioxide, the deeper the carbonation that the concrete has, especially for high volume raw fly ash concrete.

Nevertheless, high strength concrete shows its excellent resistance to carbonation deterioration as only a negligible part of concrete is being carbonated. The result is in line with previous research of carbonation test which argues that higher strength concrete results in better carbonation resistance (Hui-sheng et al., 2009, Khana and Lynsdale, 2002)..

Moreover, there is no influence of fibre type used for the depth of carbonation as carbon in atmosphere only reacts with concrete paste but not with the fibre as can be seen in carbonation chemical reaction (Formtex, 2003, Papadakis et al., 1989).

6.2.3. Sulfate resistance

In some circumstances, concrete needs to have adequate resistance to sulfate attack which mainly comes from ground water (Mehta, 1992). The mechanism of this kind of sulfate attack is known as sulfate absorption. To study the resistance of high strength concrete to sulfate attack, sulfate absorption test was conducted. This kind of test was selected considering that another sulfate resistance test method by immersing concrete specimens in sulfate solution might continue its hydration process and might produce an ambiguity in result when analysing its compressive strength loss (Kurtis et al., 2001).

The sulfate resistance of concrete was conducted at the concrete specimens' age of 180 days based on new approach of sulfate resistance prepared by Ferraris et el. (2006) and followed the procedure in ASTM C 1585 (2004). The specimens have dimension of 100 mm diameter and 50 mm height and before the test the specimens were coated with epoxy resin on curved surface and preconditioned to achieve saturation of 60%. The specimen was then put on sulfate solution and the change of mass caused by sulfate sorption along with the change of time was recorded.

Figure 6.12: Sulfate absorption test

The absorption of sulfate was calculated using the following equation (ASTM C 1585, 2004):

$$\boldsymbol{I = \frac{m_t}{a * d}}$$

Where, I = the absorption,

m_t = the change in specimen mass (gram) at the time, t

a = the exposed area of specimen (mm^2)

d = the density of water (gram/ mm^3)

Sample No	:	6 _ 2	Start testing date : 8/01/11
Sample age	:	26 weeks	Diameter (mm) : 100.18 mm
Mass of condition disc (prior to sealing side)	:	966.85 g	: 100.20 mm
			: 100.10 mm
Thickness	:	50.60 mm	: 100.20 mm
			Exposed area : 7,880.70 mm^2

$$I = \frac{m_t}{a * d}$$

Test time	s	$s^{1/2}$	mass (gram)	∆ mass (gram)	I (mm)
	0	0	967.69	0.00	0.0000
1 minute	60	7.7	967.97	0.28	0.0355
5 minute	300	17.3	968.08	0.39	0.0495
10 minute	600	24.5	968.22	0.53	0.0673
20 minutes	1200	34.6	968.39	0.70	0.0888
30 minutes	1800	42.4	968.47	0.78	0.0990
1 hour	3600	60.0	968.60	0.91	0.1155
2 hours	7200	84.9	968.90	1.21	0.1535
3 hours	10800	103.9	969.04	1.35	0.1713
4 hours	14400	120.0	969.16	1.47	0.1865
5 hours	18000	134.2	969.20	1.51	0.1916
6 hours	21600	147.0	969.31	1.62	0.2056
Day 1	86400	293.9	969.75	2.06	0.2614
Day 2	172800	415.7	970.03	2.34	0.2969
Day 3	259200	509.1	970.24	2.55	0.3236
Day 4	345600	587.9	970.44	2.75	0.3490
Day 5	432000	657.3	970.64	2.95	0.3743
Day 6	518400	720.0	970.78	3.09	0.3921
Day 7	604800	777.7	970.93	3.24	0.4111
Day 8	691200	831.4	971.03	3.34	0.4238

Figure 6.13: Sample sheet calculation of sulfate absorption

The calculation of sulfate absorption (I) for every recorded time ($s^{½}$) is summarized in a spread sheet as can be seen in **Figure 6.13**. This calculation is used to plot the correlation graph of $s^{½}$ to the absorption (I) which determines the initial and secondary rates of absorption (**Figure 6.14**). The initial rate of absorption is the linear slope of graph $s^{½}$ to the absorption (I) from the first recording until 6 hours of test. The secondary rate of absorption is the linear slope which is determined using the same manner as initial rate of absorption from 1st day to the last day of test (Byrami, 2006). The initial rate of absorption and secondary rate of absorption can only be determined if $s^{1/2}$ to the absorption (I) has minimum data correlation of R = 0.98 (ASTM C 1585, 2004).

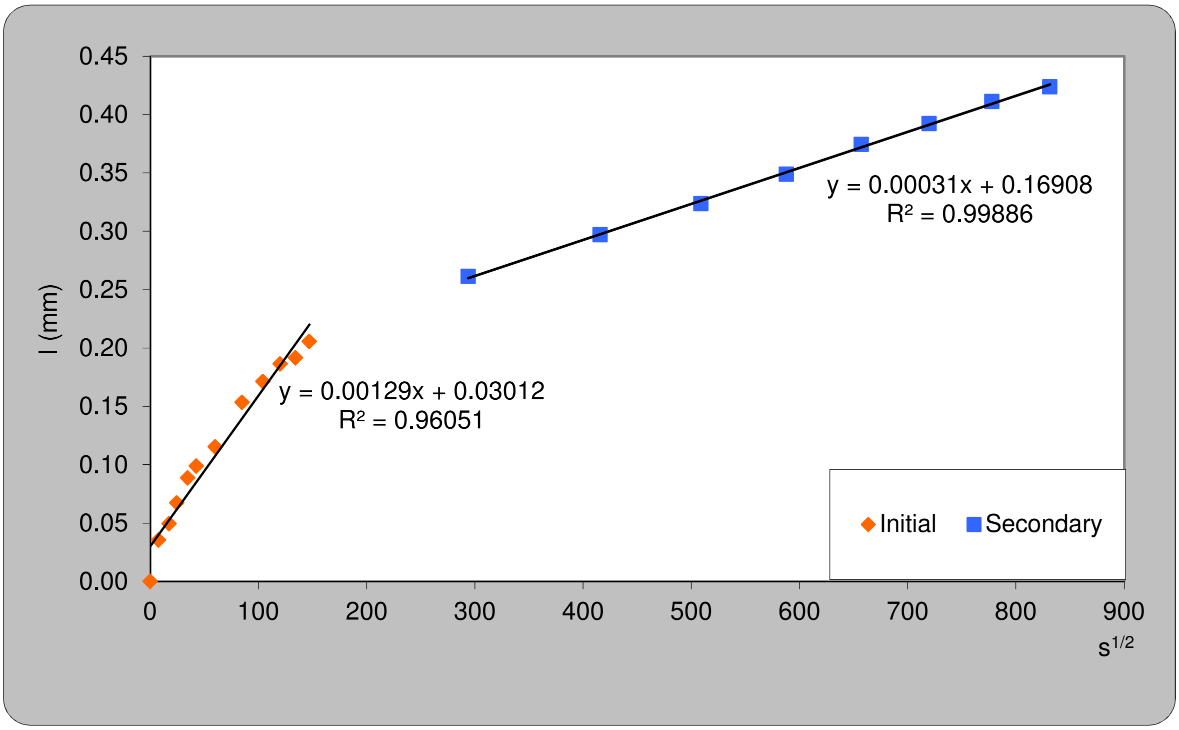


Figure 6.14: Initial and secondary rate of absorption for concrete No 6

The result of sulfate absorption test which shows both initial and secondary rate of sulfate absorption is presented in **Table 6.3**.

Table 6.3: Initial and secondary rate of sulfate absorption

	Initial rate absorption x 10^4 mm/ $\sqrt{s}$	**Secondary rate absorption x 10^4 mm/ $\sqrt{s}$**
UFFA without basalt fiber, tap water (No 1)	7.030	2.025
UFFA with basalt fiber, lime water (No 2)	7.992	1.755
Raw Fly Ash with basalt fibre, tap water (No 3)	9.546	2.160
Raw Fly Ash without basalt fibre, lime water (No 4)	7.918	1.595
OPC without fibre, tap water (No 5)	10.400	2.650
OPC with basalt fibre, tap water (No 6)	12.900	3.050
OPC with steel fibre, tap water (No 7)	11.800	2.750
UFFA without basalt fiber, lime water (No 10)	6.500	1.702

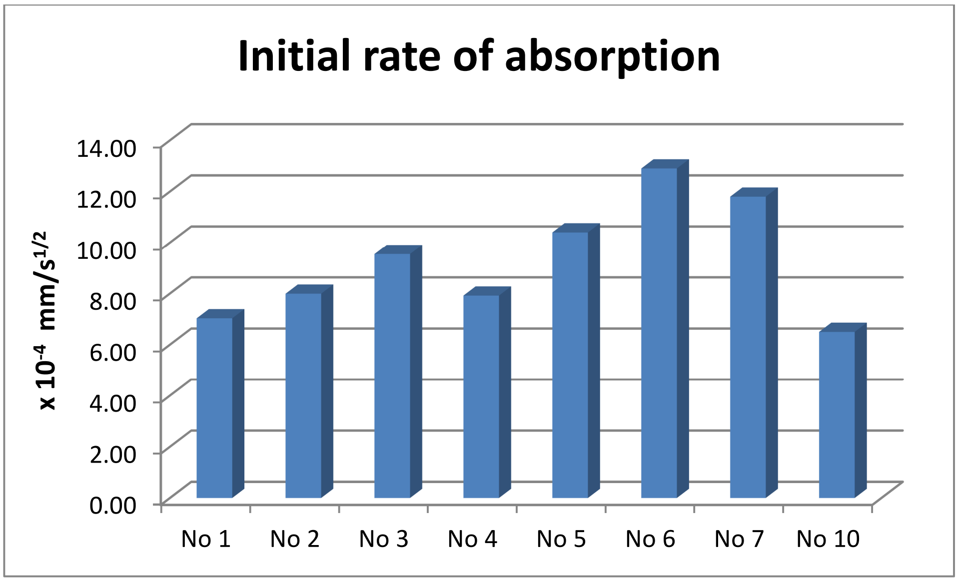


Figure 6.15: Initial rate of sulfate absorption

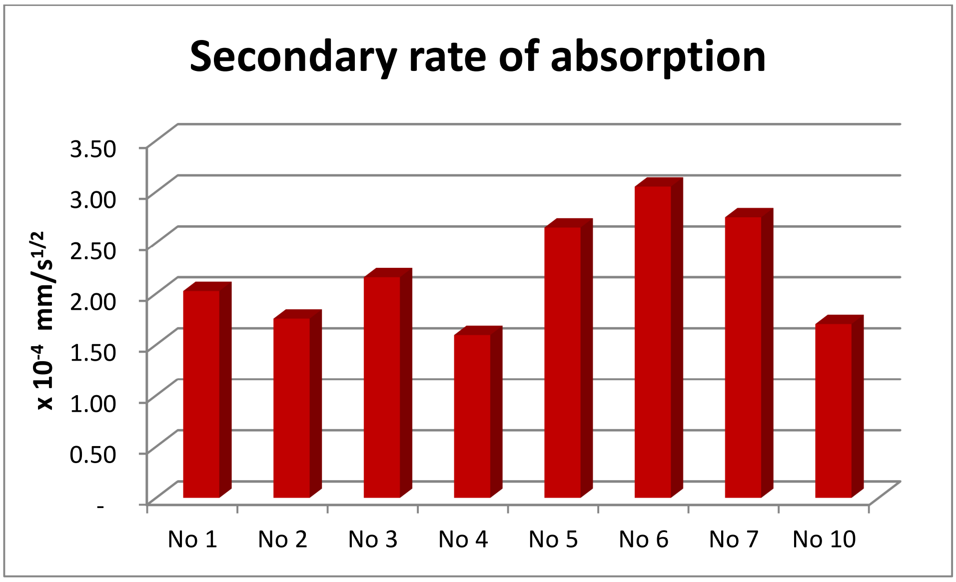


Figure 6.16: Secondary rate of sulfate absorption

The graph of initial and secondary rate of absorption (**Figure 6.15 and Figure 6.16**) shows that the secondary rate of absorption is significantly lower than the initial rate of absorption because after longer period of test, the moisture content in concrete increases and only a small amount of liquid can be absorbed. When comparing the sulfate absorption to the result of absorption rate from other researchers (**Table 6.4.**), it can be concluded that higher compressive strength produces lower rate of absorption. This result is confirmed with the rate of absorption of concrete No 7 which has lower rate of absorption in comparison to concrete No 6. (**Figure 6.15 and Figure 6.16)**.

Table 6.4: Absorption result from previous researchers

Compressive strength (MPa)	Initial rate absorption x 10^4 mm/ $\sqrt{s}$	Secondary rate absorption x 10^4 mm/ $\sqrt{s}$	references
28.6	215.0	4.0	(Byrami, 2006)
13.3	107.0	29.0	
41.4	35.2	15.3	(Lane, 2006)
51.3	23.5	11.2	
67.3	12.7	6.5	
73.2	4.8	2.3	

High volume fly ash concrete has lower rate of absorption, both for initial and secondary rate of absorption in comparison to OPC concrete which is related to apparent volume of permeable voids (AVPV) test of fly ash concrete. The lower AVPV in fly ash concrete leads to lower rate of absorption. Moreover, the lower AVPV in fly ash concrete results in excellent criteria for durability based on the criteria of concrete's durability from Vicroads (**Table 6.2**).

To understand the correlation between water absorption and sulfate absorption, the correlation of polynomial order 5 was used to find the best correlation between water absorption properties and sulfate absorption.

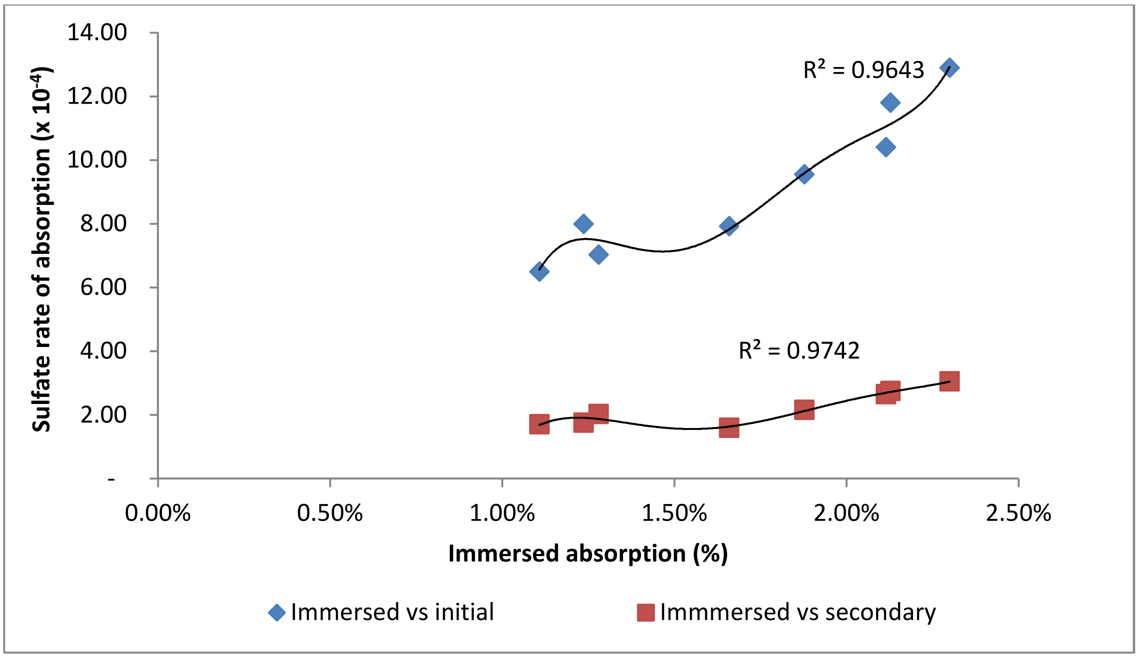


Figure 6.17: Correlation between immersed absorption and sulfate rate of absorption

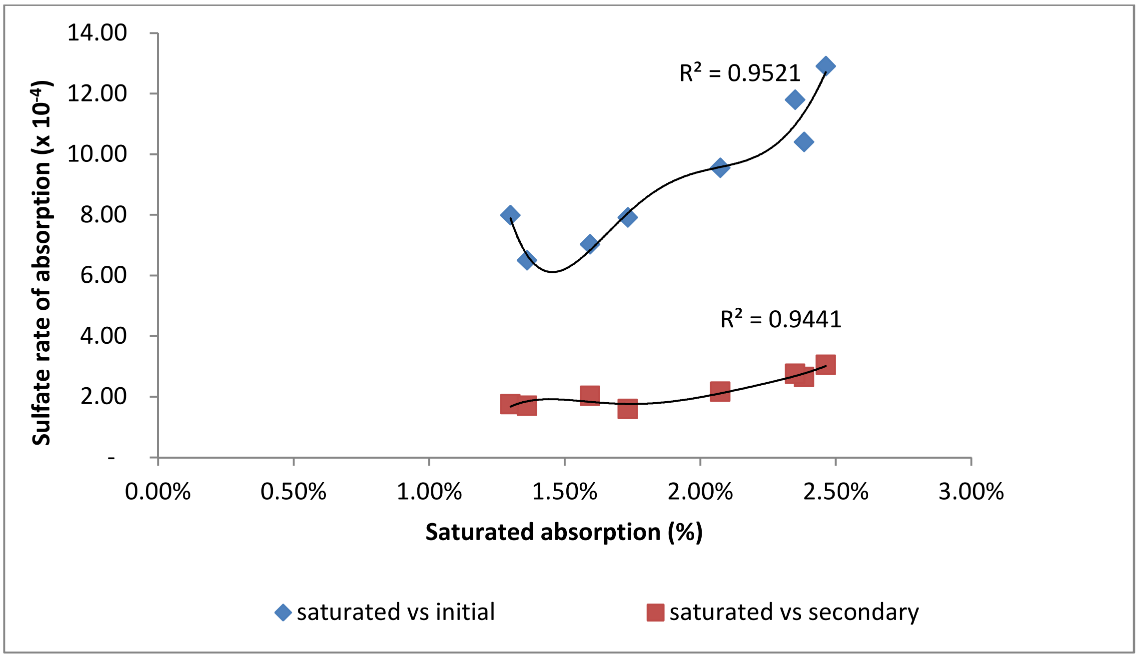


Figure 6.18: Correlation between saturated absorption and sulfate rate of absorption

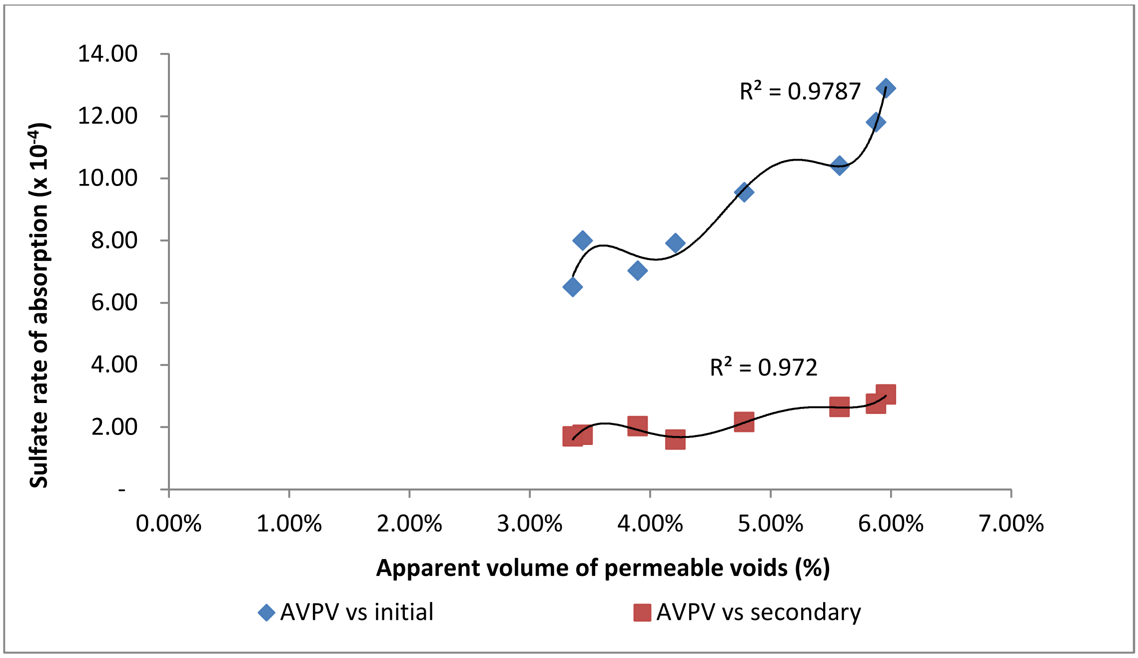


Figure 6.19: Correlation between AVPV and sulfate rate of absorption

From those correlation graphs, the best correlation is correlation between immersed absorption and apparent volumes permeable voids and sulfate rate of absorption as the R^2 value for both correlations is the highest. Consequently, the result of immersed absorption or AVPV can be used to make prediction of sulfate rate of absorption.

6.2.4. Rapid chloride Penetration test

Rapid chloride penetration test (RCPT) is testing the ion migration between a 50 mm thickness of concrete specimen which is immersed in a sodium chloride on one end and the other end is immersed in sodium hydroxide solution. To accelerate the ion migration, a potential difference of 60V DC (Direct Current) is maintained across the end and the amount of electrical current, passing through the concrete during a six-hour period of test is recorded and total charge passed in coulomb is used as an indicator of the resistance of the concrete to chloride ion penetration (CCAA Report, 2009).

The study on Rapid chloride penetration test is conducted at concrete age of 56 days and 180 days for all of the specimens excluding the specimen No 7, steel fibre concrete. The exclusion of specimen No 7 is because the presence of steel in concrete will significantly affect the result as stated in ASTM C 1202-97 (2002). Nevertheless, rapid chloride penetration test for steel fibre concrete is still conducted for concrete at the age of 56 days to confirm the exclusion of the test from the standard.

Vacuum process of specimens

RCPT equipment

Figure 6.20: Rapid chloride penetration test (RCPT)

The test was conducted for both testing ages (56 days and 180 days) to study the effect of hydration development to resistance of chloride penetration of concrete. Moreover, the two different testing ages were conducted only for RCPT considering that the rapid chloride penetration test is widely accepted as the test for concrete durability (Hameed et al., 2010, Hooton et al., 2001, Joshi and Chan, 2002). The other durability tests are not found in the literature as frequently as RCPT.

The result of RCPT, that shows the charge passed (coulombs) for all the specimens is presented in **Figure 6.21** for testing age of 56 days and 180 days. The result of the test was compared to the qualitative resistance to chloride penetration table of ASTM C 1202-97 (ASTM C 1202 -97., 2002) as can be seen in **Table 6.5**.

Table 6.5: Level of cloride ion penetrability based on charge passed (ASTM C 1202 -97., 2002)

Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very Low
<100	Negligible

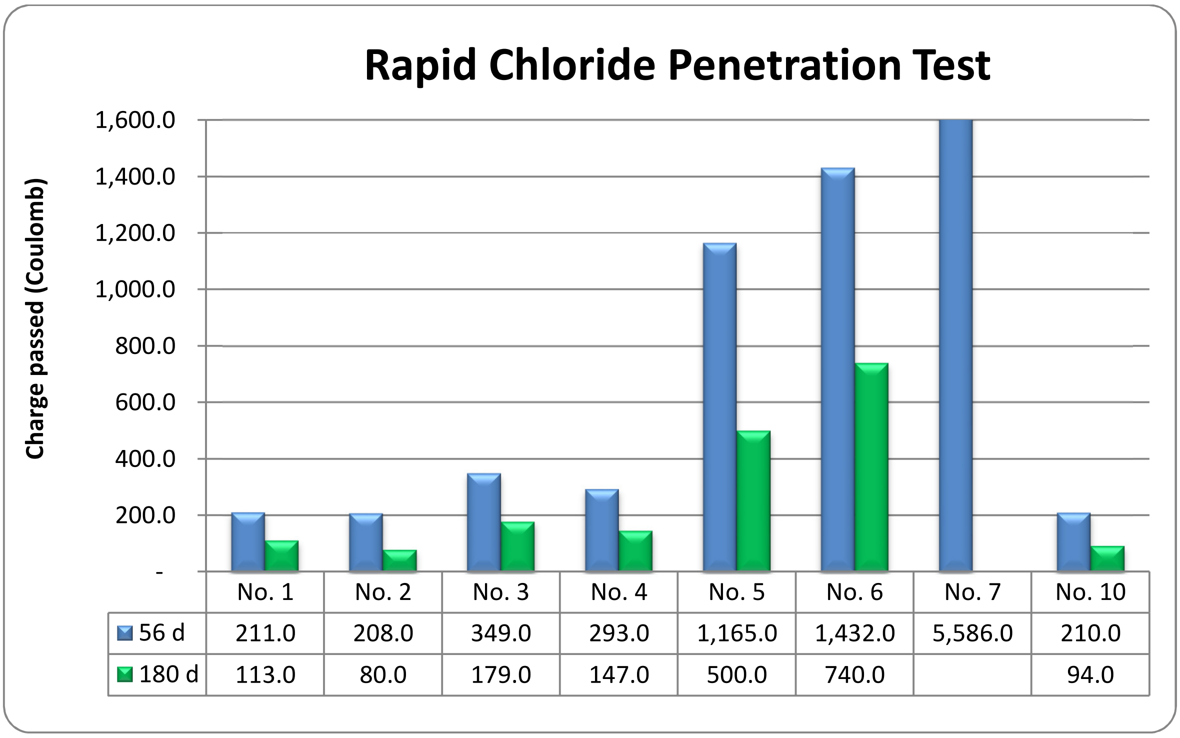


Figure 6.21: Rapid chloride penetration test result

The result of RCPT shows that the concrete using steel fibre cannot be used to investigate the resistance of the concrete from chloride attack, considering that the use of electric current to steel fibre as it makes the charge passed very high. Therefore, the RCPT for steel fibre concrete was only conducted at the age 56 days.

Moreover, the longer testing age increased resistance to chloride penetration. This resistance indicates that the hydration process of concrete still continues after concrete curing for 56 days up to the testing age of 180 days. The increase of chloride resistance along with the increase of concrete ages is beneficial especially for high strength OPC concrete whose criteria of chloride resistance increases from low penetrability at 56 days to very low at 180 days. This result is supported by (KHAN and ALSAYED, TB-100, 2006) who also confirmed about the increase of chloride resistance with the increase of testing ages.

High volume fly ash concrete has better resistance to chloride penetration in comparison to high strength OPC concrete and it has low chloride ion penetrability criteria starting at 56 days and beyond. On the contrary, high strength OPC concrete needs 180 days of testing age to have the same criteria. Hence, it can be argued that the deployment of high volume fly ash as cementing material increases concrete resistance to chloride ingress and the result confirms the research result which was conducted by Nath and Sarker (2011).

Further increase of chloride resistance can be seen in the combination of using high volume ultra fine fly ash and using lime water that increases the criteria of chloride resistance from very low at 56 days of testing age to negligible at 180 days of test. The negligible rating of RCPT shows the combination of ultra fine fly ash and lime water enables concrete to have advance resistance to chloride ingress which is same as the resistance of polymer impregnated concrete and polymer concrete (Shi, 2003). However, it is noted here that the polymer impregnated concrete production needs a complicated process to fill concrete voids with a polymer to make the durability of concrete improve significantly (Mehta and Monteiro, 2006).

The correlation of water absorption properties and rapid chloride penetration test were analysed using same manner as correlation for sulfate resistance. The result is presented in the following graph (**Figure 6.22 and Figure 6.23**):

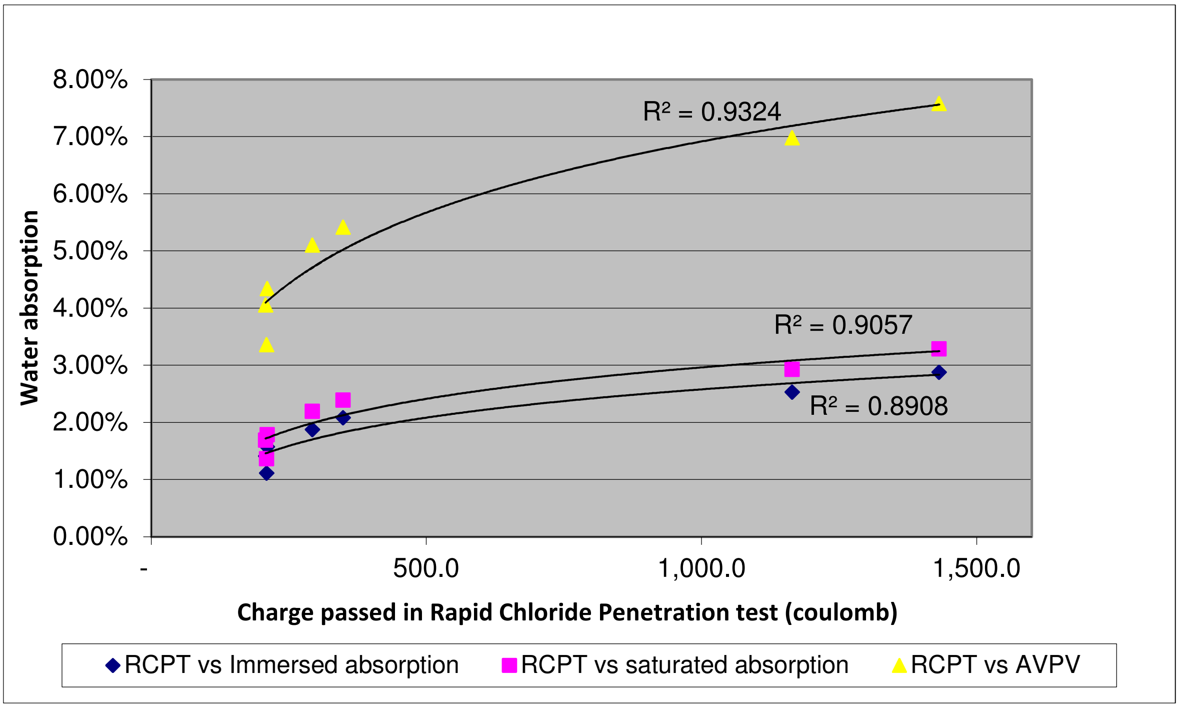


Figure 6.22: Correlation between water absorption properties and RCPT at 56 days

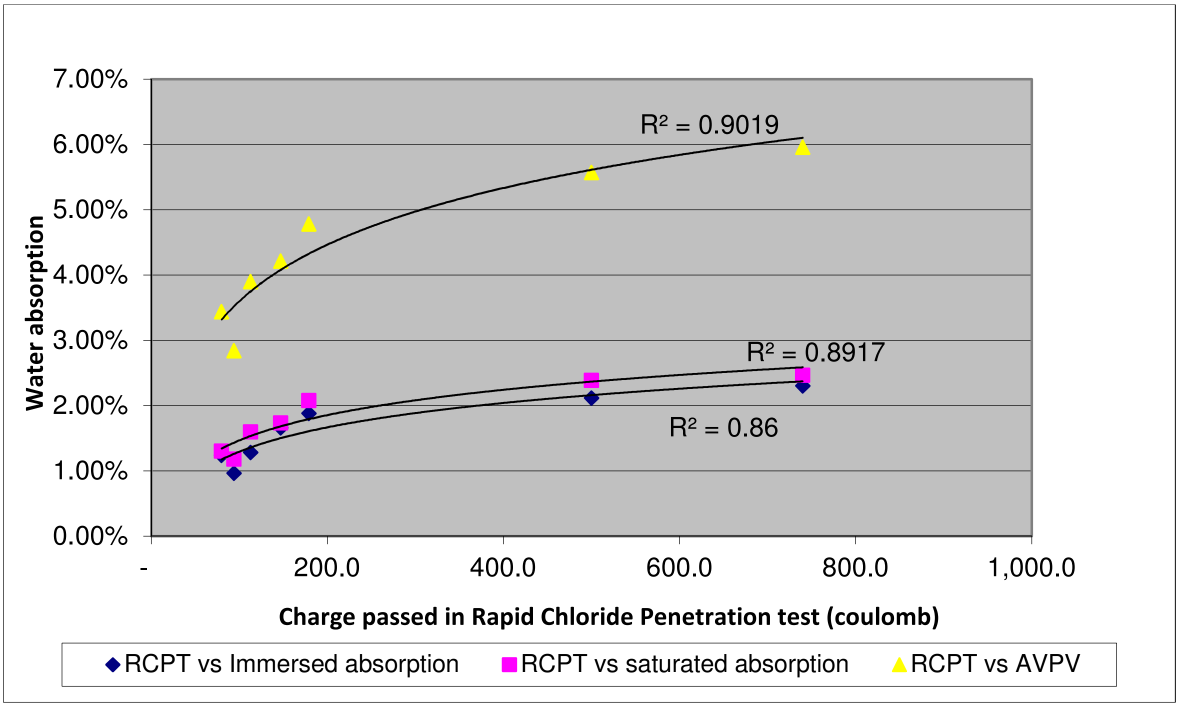


Figure 6.23: Correlation between water absorption properties and RCPT at 180 days

From the correlation of water absorption and Rapid Chloride Penetration Test (RCPT), the apparent volume of permeable voids becomes the most reliable criteria for chloride ingress as the R^2 value is the highest of water absorption properties. Also, the lower AVPV of concrete will result in better resistance to chloride ingress.

6.3. Microstructure analysis

The hydration process of binder in concrete is a complex chemical reaction especially in the first 24 hours after casting which involves the dissolution of several solid reactants phases (e.g.: C_3A and gypsum) and the growth of new substances (e.g.: C-S-H and ettringite) (LUTTGE, 2011). As the hydration product gives effect on properties of hardening concrete such as concrete durability**,** it is important to study the hydration product of binder to understand the properties of concrete in micro scale (Schutter, 2002, Scrivener, 2009).

Modern equipment (e.g.: SEM and EDAX) has enabled the microstructure study of concrete so that the result is more accurate and understandable. The microstructure analysis in this experiment comprises analysis on microstructure and chemical composition of binder paste and qualitative analysis on the microstructure of mortar and concrete.

6.3.1. Microstructure analysis of binder

In cement hydration process C-S-H is the main product of hydration and it is very important as a substance which gives strength to concrete (Mehta and Monteiro, 2006). Besides, former study of researchers found that some of physical and chemical substances of the C-S-H are affected by the Ca/Si ratio. For instance, density and specific surface area of C-S-H is influenced by Ca/Si ratio. It is also found that there is a correlation between Ca/Si ratio and chloride adsorption in C-S-H (Saeki and Sasaki, 2008).

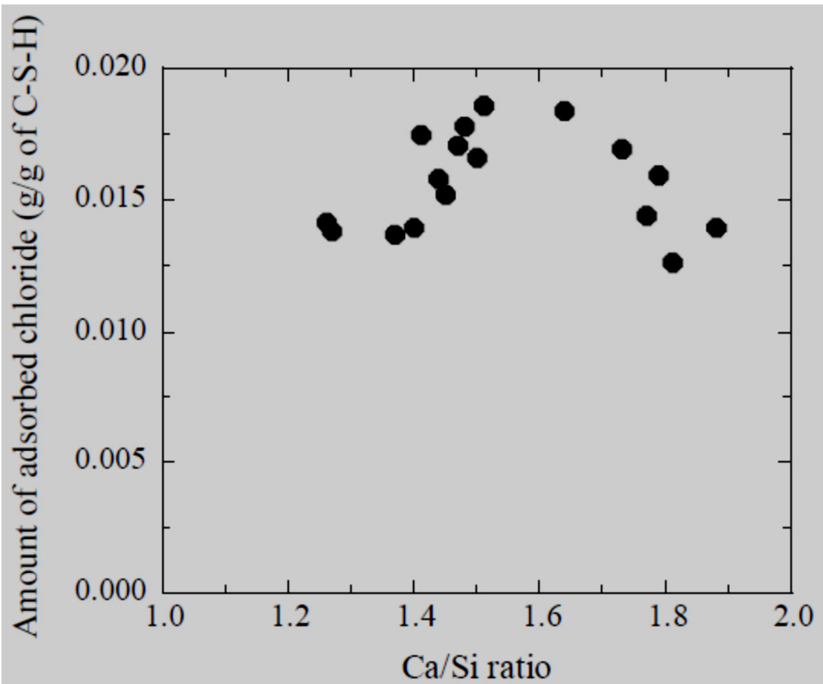


Figure 6.24: Effect of Ca/Si ratio on the amount of adsorbed chloride in C-S-H (Saeki and Sasaki, 2008)

In this study, the microstructure analysis on binder was focused on formation of binder paste structure and concentration of chemical formation especially Calcium (Ca) and Silica (Si). To analyse the chemical composition of binder after hydration process, microstructure analysis was conducted on the following combinations of binder:

a) OPC paste.
b) High volume raw fly ash paste.
c) High volume ultra fine fly ash paste using saturated lime water.

The specimens for microstructure analysis were prepared by cutting a fractured specimen with a diameter of around 1 cm and the thickness of 2 mm cast and then attached to carbon conductive material. In the preparation of specimens before SEM observation, the surface of specimens was ground using sand paper and using laminated diamond polishing which has size of 9 microns, 3 microns and 1 micron subsequently. In the last stage of the specimen preparation, the specimens were coated with carbon using a sputter coating machine.

The microstructure analysis utilized scanning electron microscope (SEM) analysis on a small piece of specimen under Philips XL 30 SEM to understand the micro structure of the specimens. The analysis was continued using EDAX (energy dispersive analysis X-ray) analysis to find out the chemical composition as a result of hydration.

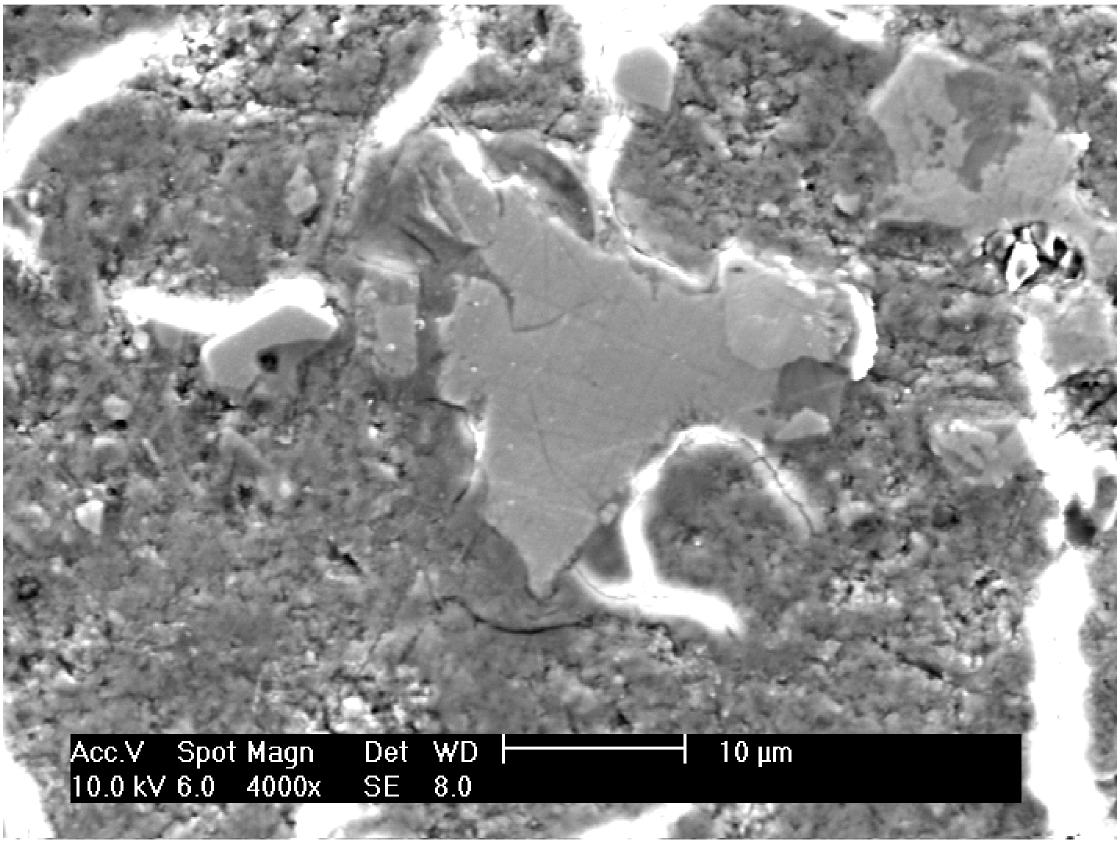


Figure 6.25: SEM of OPC paste

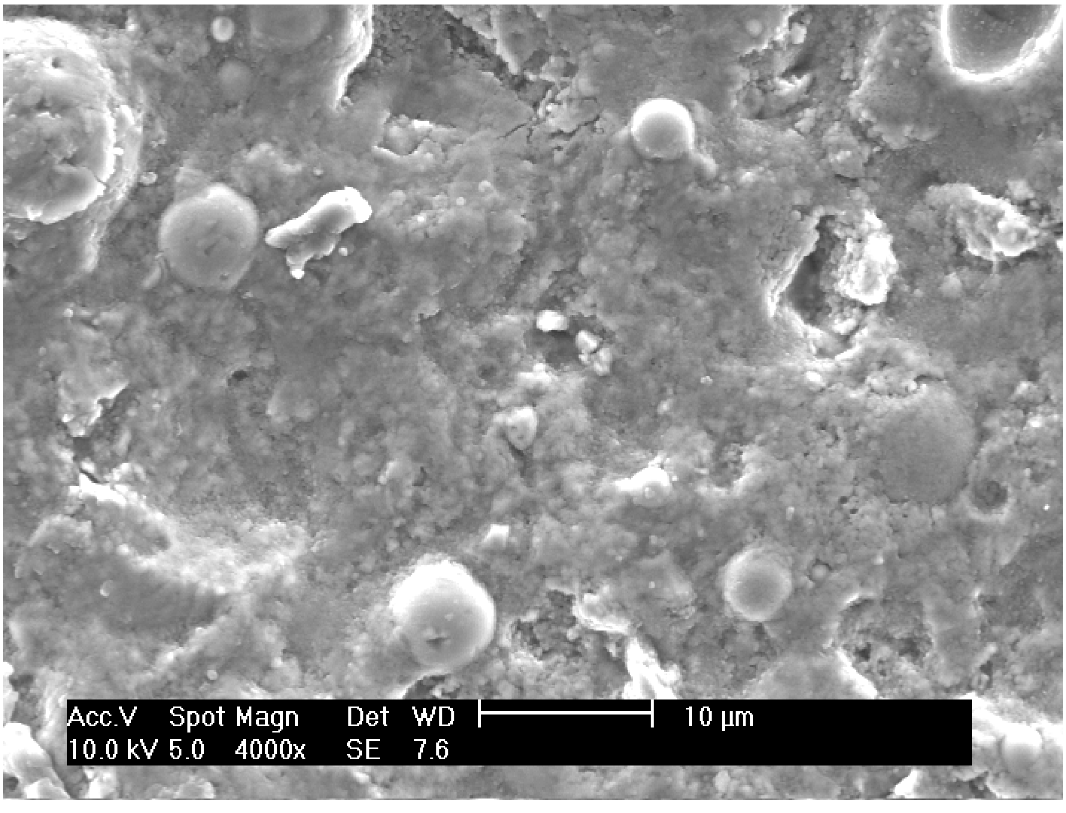


Figure 6.26: SEM of High volume raw fly ash paste

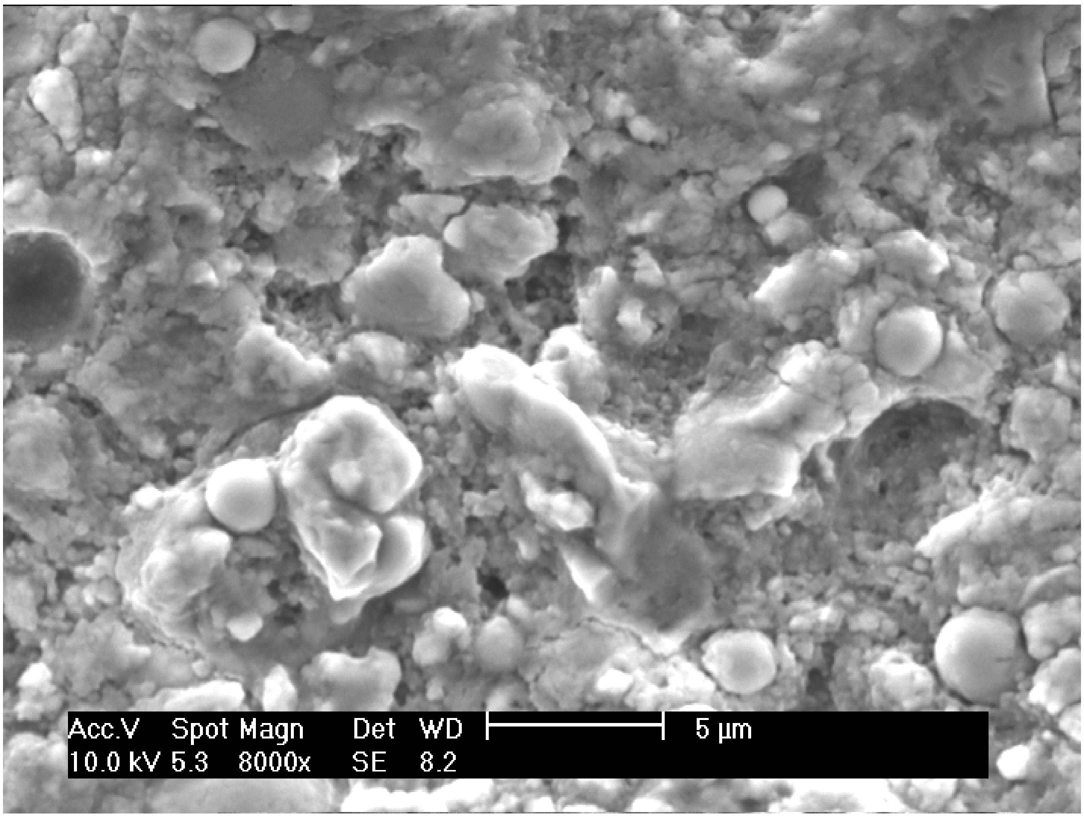


Figure 6.27: SEM of High volume ultra fine fly ash paste using saturated lime water

The pictures of SEM binder (**Figure 6.25-6.27**) show the different formation of C-S-H for different types of binder. The OPC paste has large structure and smoother layer of C-S-H in comparison to fly ash paste. Although the fly ash binder has coarse layer in comparison to OPC binder, the fly ash concrete has less voids as can be seen by the lesser black colour which indicates capillary pores (Bentz and Stutzman, 2006). The un-hydrated particles of fly ash also confirm that high volume raw fly ash concrete has bigger fly ash particles in comparison to high volume ultra fine fly ash.

Although the high volume ultra fine fly ash paste does not have big smooth C-S-H layer as OPC paste, the combination of small layers made its structure stronger, similar to OPC paste. The chemical concentration of Calcium (Ca) and Silica (Si) for those binder pastes are summarized in **Table 6.6.**

Table 6.6: Hydration product of binder (% by mass)

	OPC	High volume raw fly ash	High volume ultra fine fly ash with saturated lime water
Al_2O_3	6.50	17.84	7.78
SiO_2	39.13	39.95	37.16
P_2O_5	8.69	13.21	18.20
SO_3	6.98	1.79	4.25
CaO	38.69	27.21	32.61
Ca/Si ratio	0.989	0.681	0.878

The analysis of chemical content in the binder shows, the OPC paste has highest Ca/Si ratio in comparison to fly ash paste. This lower Ca/Si ratio of fly ash binder is due to the high content of silica material in fly ash which binds the $Ca(OH)_2$. Moreover, the use of lime water increases Ca/Si ratio in high volume ultra fine fly ash paste and it is beneficial in increasing the durability of concrete especially from carbonation ingress. The decrease of Ca/Si ratio has been explored by previous researchers showing that the ratio will decrease together with the increase of mineral admixture content as cement replacement (Jing et al., 2004, Monteiro et al., 1997).

6.3.2. Microstructure of mortar

To understand mortar microstructure the following specimen were prepared to observe microstructure formation of mortar:

a) OPC mortar.

b) High volume raw fly ash mortar.

c) High volume ultra fine fly ash mortar

d) High volume ultra fine fly ash mortar using saturated lime water.

The specimens were prepared in the same manner of binder specimens but it was derived from fractured specimen of mortar. The observation was conducted under FEI Quanta 200 ESEM (environmental scanning electron microscope) equipment to make qualitative analysis of mortar.

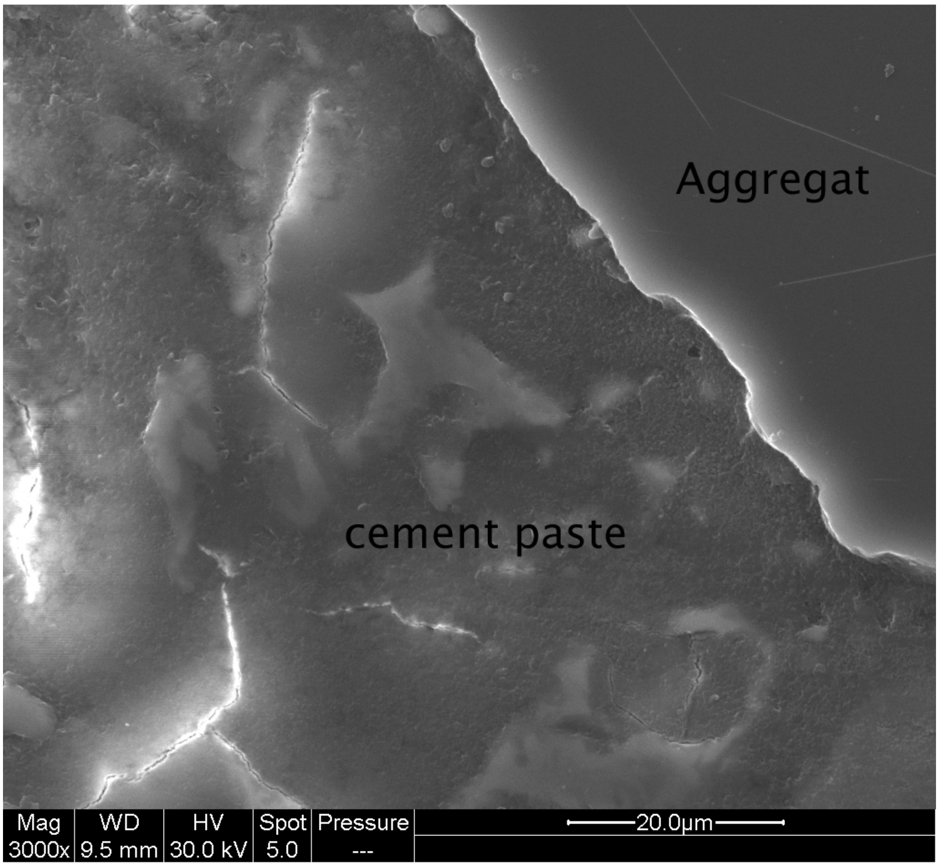


Figure 6.28: SEM of OPC mortar.

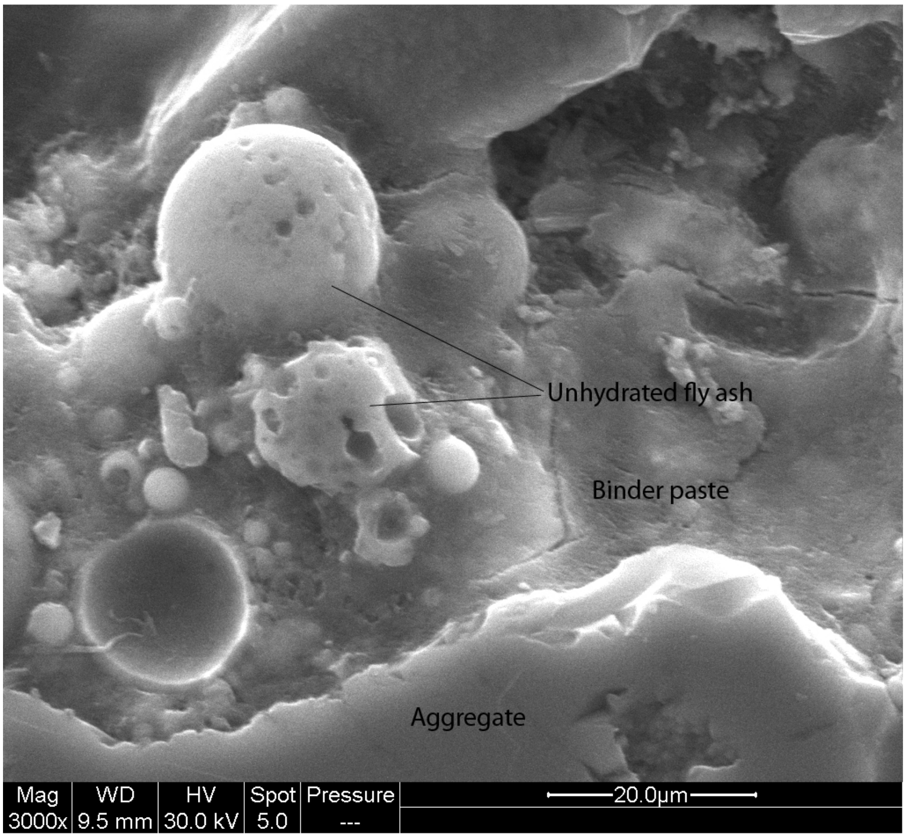


Figure 6.29: SEM of High volume raw fly ash mortar

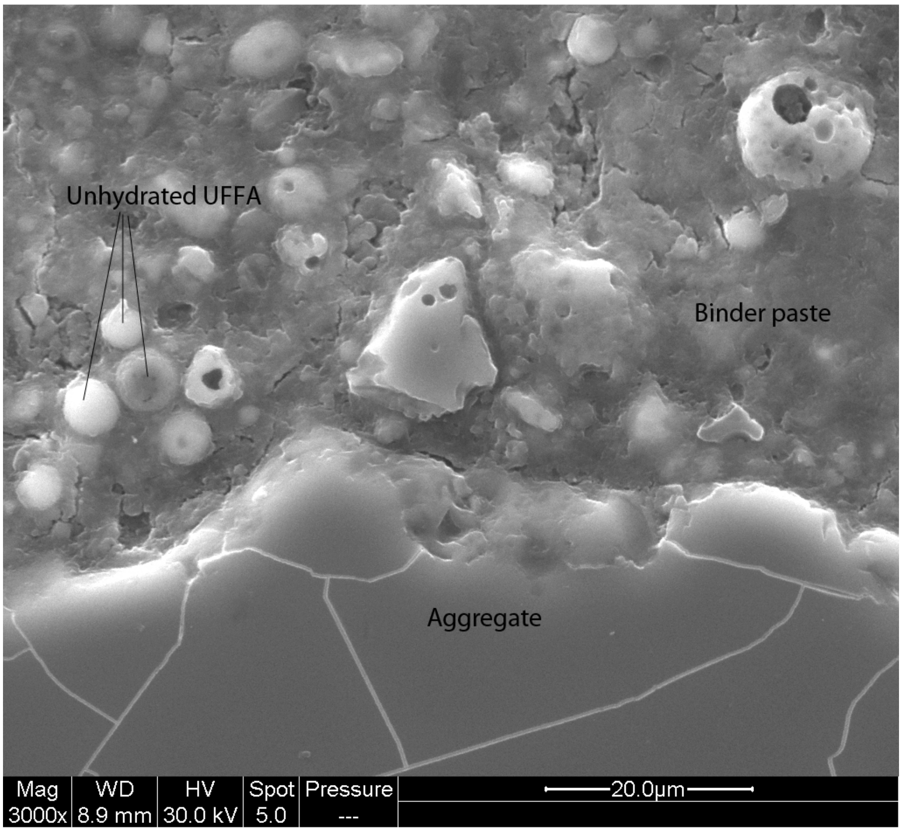


Figure 6.30: SEM of high volume ultra fine fly ash mortar

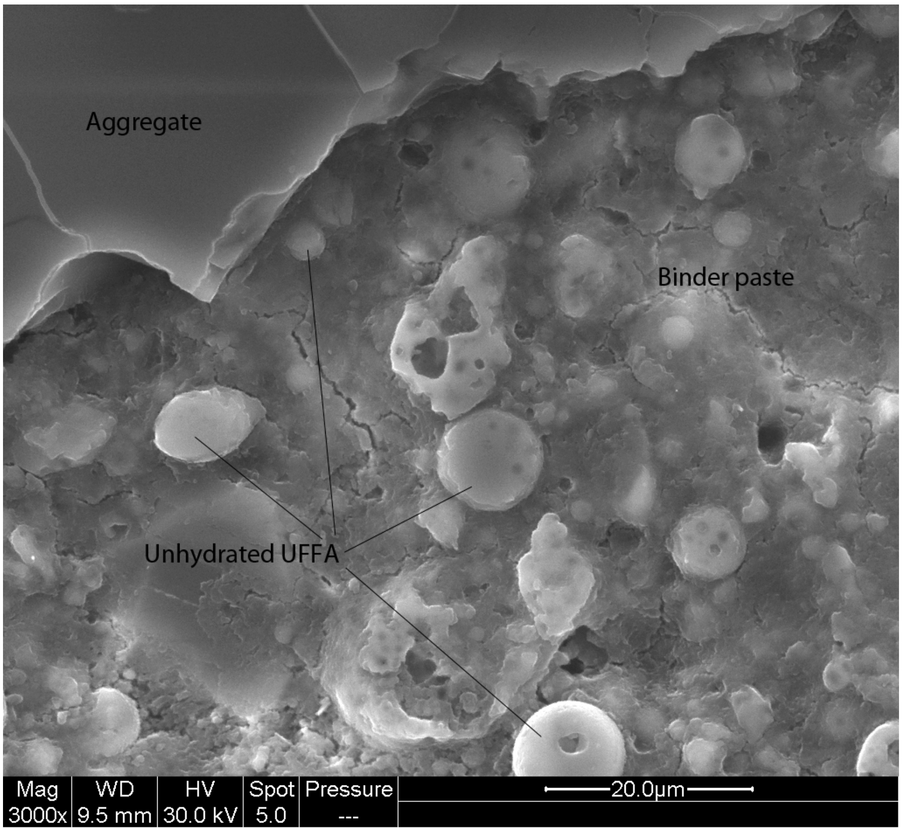


Figure 6.31: SEM of High volume ultra fine fly ash mortar with saturated lime water

The mortar SEM pictures (**Figure 6.28 to Figure 6.31**) show the different paste structure between OPC mortar and high volume fly ash mortar. The OPC mortar has smooth surface after hydration in comparison to high volume fly ash mortar. The coarse surface of high volume fly ash mortar paste is caused by un-hydrated fly ash particle (spherical shape) which still appears on the surface.

Moreover, the mortar paste of high volume raw fly ash shows some larger un-hydrated fly ash particles in comparison to ultra fine fly ash mortar paste. The larger un-hydrated fly ash particles make the paste of raw fly ash mortar less smooth than the paste of ultra fine fly ash mortar. Hence, this might becomes the reason for the lower strength of high volume raw fly ash mortar in comparison to high volume ultra fine fly ash mortar. Some micro cracks are also found on fly ash mortar.

6.3.3. SEM of fly ash concrete

The observation on concrete microstructure was divided into two sections, i.e. scanning electron microscope of lime water concrete and observation of fibre in different concrete mix proportions.

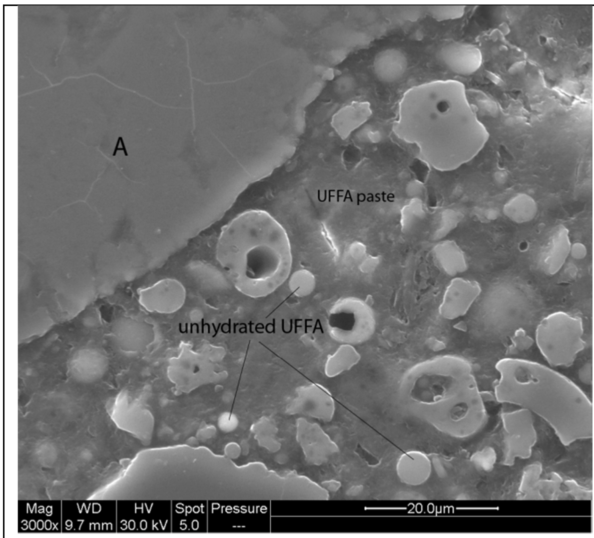
6.3.3.1. SEM of lime concrete

Figure 6.32 shows the result of scanning electron microscope observation on concrete which used lime water as mixing water. In addition, the SEM of high volume ultra fine fly ash using tap water and high strength OPC are also presented as comparison. There are 4 specimens prepared :

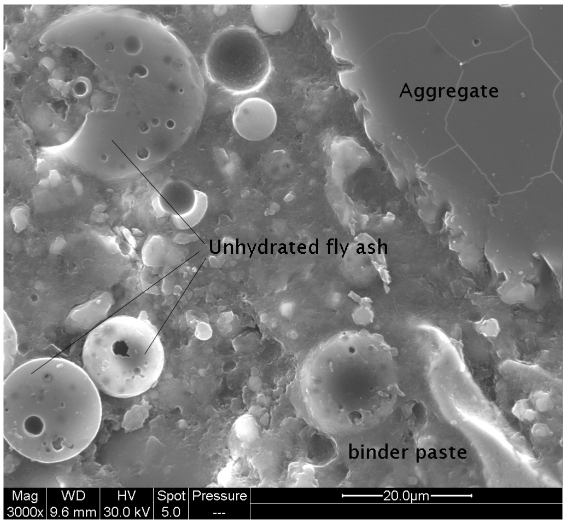
a). High volume ultra fine fly ash (UFFA) concrete using lime water as mixing water (No 10)

b). High volume raw fly ash concrete using lime water as mixing water (No 4) c). High volume ultra fine fly ash using tap water as mixing water (No 1)

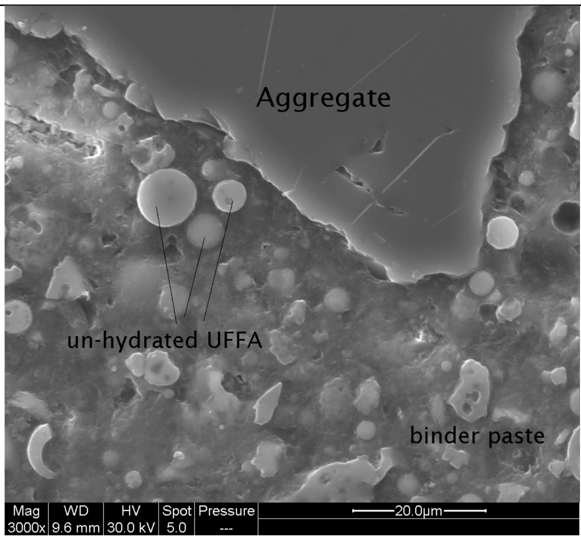
d). High strength OPC concrete without fibre using tap water as mixing water (No 5)



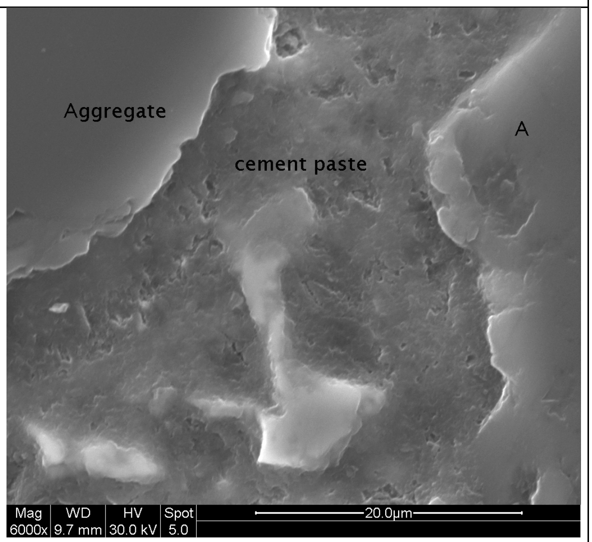
SEM of concrete No. 10



SEM of concrete No 4



SEM of concrete No. 1



SEM of concrete No. 5

Figure 6.32: SEM of lime concrete

Figure 6.32 show the surface of all of the concretes has a good structure density which indicates strong and low permeable material. The pastes bind the aggregate very well as transition zone in border area between binder paste and aggregate is hardly found. Besides, high volume fly ash concretes clearly show the residue of un-hydrated fly ash on the paste which is different from OPC concrete whose cement paste are smooth and clear.

Moreover, in high volume raw fly ash (**SEM No. 4**), it can be found more porous area on un-hydrated fly ash and paste in comparison to ultra fine fly ash concrete and OPC concrete. The porous media makes the strength of raw fly ash concrete lower than ultra fine fly ash concrete and OPC concrete.

6.3.3.2. SEM of fibre in concrete

The microstructure observation of fibre concrete was conducted on three different specimens, i.e:

a). High volume raw fly ash concrete using basalt fibre (No 3)

b). High strength OPC concrete using basalt fibre (No 6)

c). High strength OPC concrete using steel fibre (No 7)

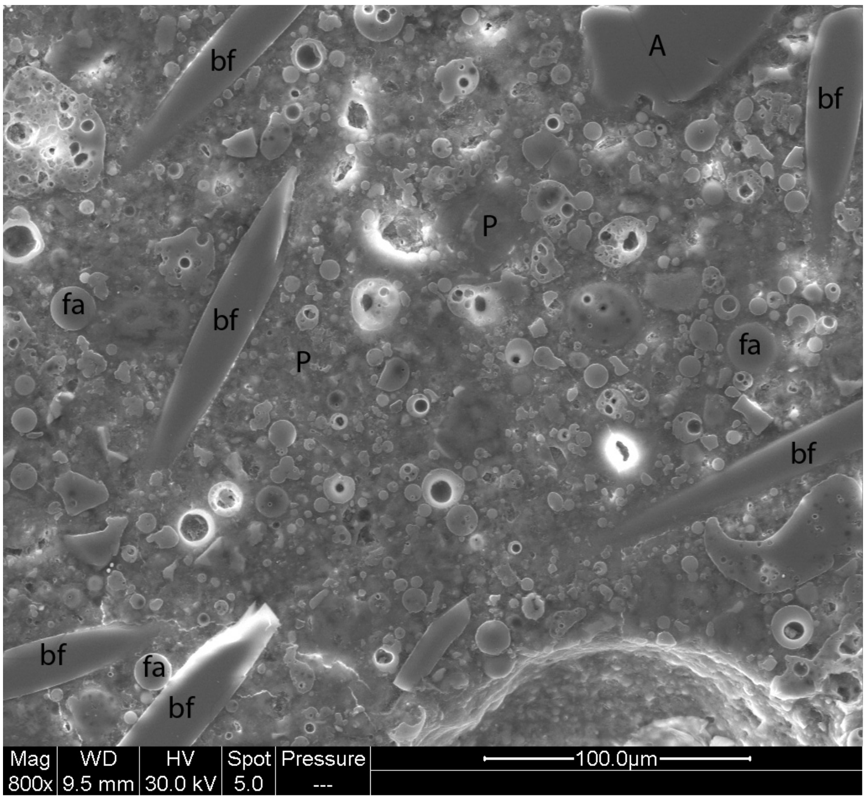


Figure 6.33: SEM of High volume raw fly ash concrete using basalt fibre

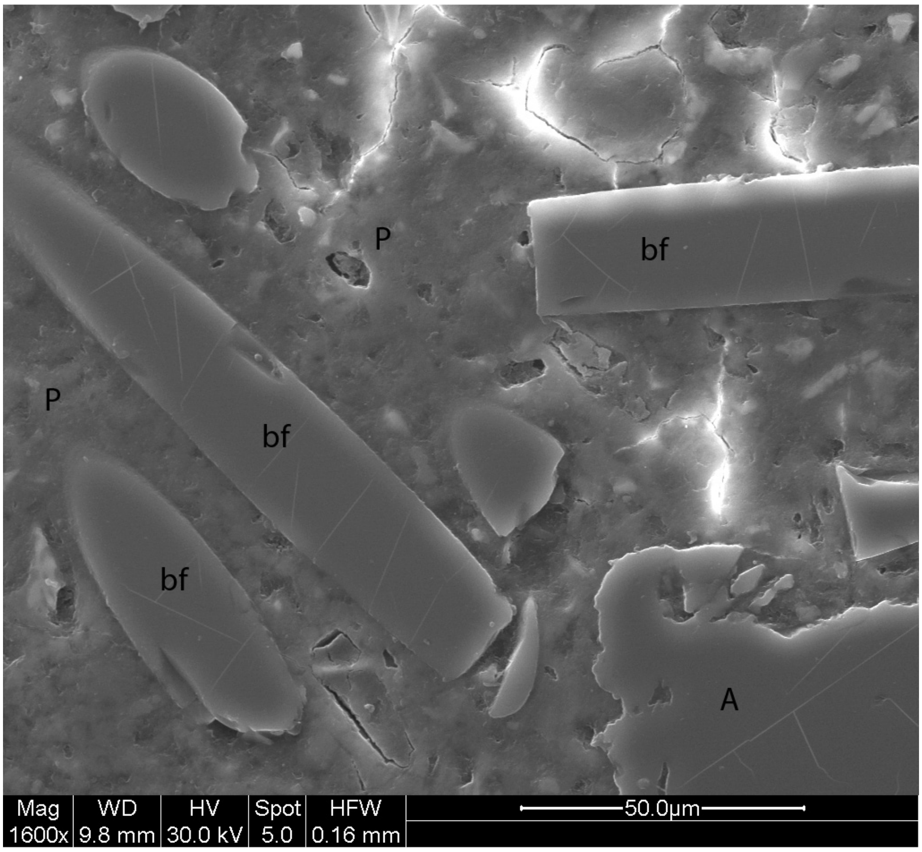


Figure 6.34: SEM of high strength OPC concrete using basalt fibre

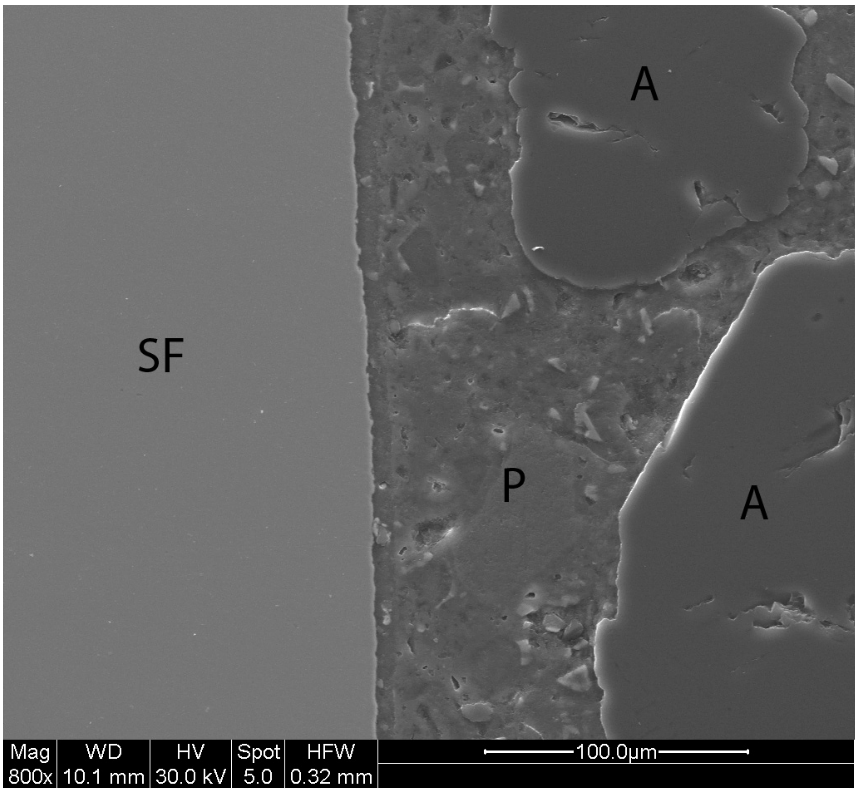


Figure 6.35: SEM of high strength OPC concrete using steel fibre

The pictures in **Figure 6.33** and **Figure 6.34**, show the remaining basalt fibre in concrete with the diameter of individual strand of 20 micrometres which is same as the data sheet properties of the basalt fibre (**Table 3.4**). The SEM of steel fibre which has large size in OPC matrix is presented in **Figure 6.35**.

The remaining basalt fibre confirms the brittleness of basalt fibre in cement matrix. It is indicated by the strands that are discretely distributed into the cement paste and the length of basalt fibre pieces that show the fibre is cut randomly. In addition, the picture of basalt fibre is different from the picture of steel fibre which shows the steel fibre's original shape and size in cement matrix.

6.4. Summary of chapter 6

Having discussed the durability test and microstructure analysis of high volume fly ash concrete, it can be summarized that:

1 In comparison to OPC concrete high volume fly ash concretes has lower water absorption properties and a further reduction in water absorption when combination of ultra fine fly ash and lime water as mixing water were used.

2 The lower water absorption properties protect the high volume fly ash concretes from the influence of aggressive environmental substance and lead to the increase of concrete durability. On the contrary, the carbonation test shows that high volume fly ash in concrete bounds carbon from atmosphere promptly than OPC concrete. This disadvantage, however; can be reduced by using the combination of ultra fine fly ash and lime water as mixing water which significantly decrease carbonation attack in high volume fly ash concrete.

3 In regard to water absorption properties, the apparent volume of permeable voids (AVPV) becomes the best properties to describe the concrete durability

in which the lowest AVPV leads to the superior concrete durability properties. This result confirms the durability criteria of concrete based on AVPV.

4 The microstructure analysis shows OPC paste has smooth surface in comparison to high volume fly ash paste which is due to un-hydrated fly ash. Moreover, the larger un-hydrated fly ash particles make the paste of raw fly ash mortar less smooth than the paste of ultra fine fly ash mortar and this might become the reason for the lower strength of high volume raw fly ash mortar in comparison to high volume ultra fine fly ash mortar.

5 Different from steel fibre in concrete, the degradation of basalt fibre in concrete can be found under microstructure analysis showing that basalt fibre changes into small parts which are different from its original form. Meanwhile, steel fibre still shows its original shape which has bigger dimension and therefore, is better as a strengthening material.

7. Conclusion and recommendation for further research

7.1. Conclusions

This research investigated the utilization of high volume ultra fine fly ash concrete to produce high strength concrete icorporating basalt fibre as strengthening material for concrete. The research also examined the use of lime water as mixing water for high volume fly ash concrete which has not been investigated by any previous research.

Based on the results of the analysis, the research has drawn some conclusion:

1) After grinding the raw fly ash in the micronizer, the fineness of fly ash is increased by 40% and has smaller particle size than that of the raw fly ash.
2) Examining the effect of low w/binder ratio and ultra fine fly ash content on compressive strength of mortar revealed that, the ultra fine fly ash content is more influential than low w/b ratio on the mortar compressive strength.
3) The use of saturated lime water as mixing water gives significant improvement in compressive strength development of high volume ultra fine fly ash mortar which is similar to the strength of OPC mortar at early ages. The compressive strength of high volume UFFA mortar with saturated lime water is higher than that in OPC mortar strength at the age of 56 days. However, the flexural strength development of high volume UFFA mortars is lower than OPC mortar.
4) Water absorption properties of high volume ultra fine fly ash mortar with saturated lime water as mixing water was the superior compared to all different types of mortar examined here.

5) In concrete mix proportioning, the use of ultra fine fly ash and the use of lime water respectively become the two most important factors to increase compressive strength of high volume fly ash concrete.
6) The combination of both factors (high volume ultra fine fly ash and lime water) can be proposed to produce high strength concrete which has similar strength as OPC concrete starting at the concrete age of 28 days and beyond.
7) The use of basalt fibre as strengthening material in concrete decreases the compressive strength of the concrete as a result of basalt fibre's lower volumetric stability in alkali environment such as concrete. At early ages, basalt fibre slightly increases concrete's modulus of rupture. Nevertheless, after a longer period the concrete's modulus of rupture is also reduced due to the degradation of basalt fibre in alkaline environment.
8) In addition, the modulus of elasticity of all concrete mix proportions meets the standard correlation of compressive strength and modulus of elasticity from ACI.
9) All the high strength concrete in this research has low water absorption properties, especially when measured using apparent volume of permeable voids which fulfils the excellent criteria of durability.
10) The carbonation test of fly ash concrete shows the use of high volume fly ash as cement replacement increases the carbonation attack in concrete. However, the use of lime water as mixing water is beneficial to decrease carbonation deterioration.
11) The decrease of voids in high volume fly ash concrete significantly increases the resistance of concrete to sulfate absorption and increases the resistance to chloride attack.

12) The combination of using high volume fly ash concrete and lime water can produce high strength concrete with high performance properties as it increases compressive strength development and enhances the durability of concrete.

7.2. Recommendation for further research

During this study, a number of issues were raised on the possible improvement on properties of high performance concrete with high volume ultra fine fly ash reinforced with basalt fibre. However, due to the time constraints, not all of them can be investigated. Hence, future study needs to be conducted to get more improved properties concerning the use of high volume ultra fine fly ash as cement replacement and the utilization of lime water as mixing water i.e.

1) In high volume ultra fine fly ash mortar which uses saturated lime water as mixing water, the compressive strength of mortar is higher at testing age of 56 days. Nevertheless, when lower concentration of lime water was used as mixing water in high volume ultra fine fly ash concrete, the compressive strength of concrete is similar to OPC concrete. Further investigation needs to be conducted to study different concentration of lime water as mixing water and the grade of aggregate combination in high volume ultra fine fly ash to achieve optimum concrete's compressive strength.
2) The utilization of lime water as mixing water adopts the geopolymer mix proportion whose preference is the use of class F fly ash. However, hydration in high volume ultra fine fly ash concrete is not as complex as geopolymer concrete and the comparative study on the use of another class, class C Fly ash, would be beneficial.

3) Further durability properties need to be investigated to ascertain some enhanced durability test result of high volume ultra fine fly ash concrete using lime water as mixing water.
4) Further study on different high volume ultra fine fly ash content to produce optimum high strength-high performance concrete using lime water as mixing water needs to be carried out along with the utilization of fibre to balance the concrete's brittleness.
5) The utilization of basalt fibre as strengthening material in high strength high volume ultra fine fly ash concrete is important, however; due to basalt fibre's degradation in alkali environment, further study to increase stability of basalt fibre in concrete needs to be investigated.

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Appendices

Appendix A. Blaine air permeability test to find out the fineness of material

Material	weight of materials (gram)	Ss (m^2/kg)	Ts (s)	T ' $_{1-2}$ (s)	T $_{1-2}$ (s)	S (m^2/kg)
Cement	2.89	377.4	92.20	107.10	107.87	408.21
				107.70		
				108.80		
Raw fly ash	2.13	408.21	107.87	87.20	85.93	364.35
				85.90		
				84.70		
Ultra fine fly ash	2.3	408.21	107.87	175.80	178.57	525.21
				177.20		
				182.70		

S_s = the specific surface area of the standard reference material (SRM)

T_s = the measured interval time of the manometer drop for the SRM

Ss and Ts are obtained from literature

(Civil Engineering Materials Laboratory, CE 305L; University of New Mexico)

Cement fineness could be determined and was used to find out the fineness of fly ash

T'_{1-2} = the measured time interval of the manometer drop for the test sample

T_{1-2} = Average of T'_{1-2}

Specific surface area (m^2/ kg)

$$S = \frac{S_s\sqrt{T}}{\sqrt{T_s}}$$

Appendix B.1: Mix proportions of ultra fine fly ash mortar content of 50% and w/b ratio of 0.35.

Based on the total volume of mortar is 1,000.0 litre

w/b ratio = **0.35**

Superplasticizer = **4** litre/m3

A. Basic mix proportions for mortar (cement, sand, air & water)

sand/ cement ratio = **2.75**

	Specific gravity	Weight (kg/m3)	Volume (litre)
1. Binder Content	**3.15**	**560.25**	177.9
2. sand	**2.59**	1,540.69	594.9
3. Air			10.0
4. water		196.09	196.1
		Total volume =	978.8

B. Replacement cement content with UFFA **50%** (by weight)

	Specific gravity	Weight (kg/m3)	Volume (litre)
1. Cement	**3.15**	280.13	88.93
2. Fly ash	**2.64**	280.13	106.11
3. Sand	**2.59**	1540.69	594.86

C. Mix Proportion of Mortar by volume

1. Cement	88.9	litre
2. fly ash	106.1	litre
3. Sand	594.9	litre
4. Superplasticizer	4.0	litre
5. Air	10.0	litre
6. water	196.1	litre
Total volume =	**1,000.0**	litre

Note :

a). Total volume should be 1,000.0 litre

b). If the total volume is not 1,000.0 litre, the cement content (A.1) should be changed

c). w/c ratio and the fly ash replacement can be changed for appropriate mix design

d). Superplaticizer content should be changed for appropriate mix design

Appendix B.2: Mix proportions of ultra fine fly ash mortar content of 20% and w/b ratio of 0.35.

Based on the total volume of mortar is 1,000.0 litre

w/b ratio =	**0.35**	
Superplasticizer =	**8**	litre/m3

A. Basic mix proportions for mortar (cement, sand, air & water)

sand/ cement ratio = **2.75**

	Specific gravity	Weight (kg/m3)	Volume (litre)
1. Binder Content	**3.15**	**563.90**	179.0
2. sand	**2.59**	1,550.73	598.7
3. Air			10.0
4. water		197.37	197.4
		Total volume =	985.1

B. Replacement cement content with ultra fine fly ash **20%** (by weight)

	Specific gravity	Weight (kg/m3)	Volume (litre)
1. Cement	**3.15**	451.12	143.21
2. Fly ash	**2.64**	112.78	42.72
3. Sand	**2.59**	1550.73	598.74

C. Mix Proportion of Mortar by volume

1. Cement	143.2	litre
2. fly ash	42.7	litre
3. Sand	598.7	litre
4. Superplasticizer	8.0	litre
5. Air	10.0	litre
6. water	197.4	litre
Total volume =	**1,000.0**	litre

Note

a). Total volume should be 1,000.0 litre

b). If the total volume is not 1,000.0 litre, the cement content (A.1) should be changed

c). w/c ratio and the fly ash replacement can be changed for appropriate mix design

d). Superplaticizer content should be changed for appropriate mix design

Appendix B.3: Mix proportions of ultra fine fly ash mortar content of 50% and w/b ratio of 0.3.

Based on the total volume of mortar is 1,000.0 litre

w/b ratio =	**0.3**	
Superplasticizer =	**6**	litre/m3

A. Basic mix proportions for mortar (cement, sand, air & water)

sand/ cement ratio = **2.75**

	Specific gravity	Weight (kg/m3)	Volume (litre)
1. Binder Content	**3.15**	**575.45**	182.7
2. sand	**2.59**	1,582.49	611.0
3. Air			10.0
4. water		172.64	172.6
		Total volume =	976.3

B. Replacement cement content with ultra fine fly ash **50%** (by weight)

	Specific gravity	Weight (kg/m3)	Volume (litre)
1. Cement	**3.15**	287.73	91.34
2. Fly ash	**2.64**	287.73	108.99
3. Sand	**2.59**	1582.49	611.00

C. Mix Proportion of Mortar by volume

1. Cement	91.3	litre
2. fly ash	109.0	litre
3. Sand	611.0	litre
4. Superplasticizer	6.0	litre
5. Air	10.0	litre
6. water	172.6	litre
Total volume =	**1,000.0**	litre

Note

a). Total volume should be 1,000.0 litre
b). If the total volume is not 1,000.0 litre, the cement content (A.1) should be changed
c). w/c ratio and the fly ash replacement can be changed for appropriate mix design
d). Superplaticizer content should be changed for appropriate mix design

Appendix B.4: Mix proportions of ultra fine fly ash mortar content of 20% and w/b ratio of 0.3.

Base on the total volume of mortar is 1,000.0 litre

w/b ratio =	**0.3**	
Superplasticizer =	**9**	litre/m3

A. Basic mix proportions for mortar (cement, sand, air & water)

sand/ cement ratio = **2.75**

	Specific gravity	Weight (kg/m3)	Volume (litre)
1. Binder Content	**3.15**	**577.65**	183.4
2. sand	**2.59**	1,588.54	613.3
3. Air			10.0
4. water		173.30	173.3
		Total volume =	980.0

B. Replacement cement content with ultra fine fly ash **20%** (by weight)

	Specific gravity	Weight (kg/m3)	Volume (litre)
1. Cement	**3.15**	462.12	146.70
2. Fly ash	**2.64**	115.53	43.76
3. Sand	**2.59**	1558.40	601.70

C. Mix Proportion of Mortar by volume

1. Cement		146.7	litre
2. fly ash		43.8	litre
3. Sand		601.7	litre
4. Superplasticizer		9.0	litre
5. Air		10.0	litre
6. water		173.3	litre
	Total volume =	**1,000.0**	litre

Note

a). Total volume should be 1,000.0 litre

b). If the total volume is not 1,000.0 litre, the cement content (A.1) should be changed

c). w/c ratio and the fly ash replacement can be changed for appropriate mix design

d). Superplaticizer content should be changed for appropriate mix design

Appendix C.1: Mix proportions of high volume ultra fine fly ash mortar

MIX DESIGN SHEET: High volume ultra fine fly ash mortar

Comp. Strength : 80 MPa

Mortar test

Table A	Spec. Gravity	%
Cement	3.15	50.00%
ultra fine fly ash	2.18	50.00%

Aggregate	G_{SSD}	% W_{abs}	W_{tot}	W_h
Coarse	2.80	2.4	0	-2.4
Fine	2.65	3.9	1.5	-2.4

$W_h = w_{tot} - w_{abs}$ $M = M_{SSD} \times (1 + w_h)$

Superplasticizer

G_{sup}	Solid dosage s (%)	$M_{sol} = C \times \frac{d}{100}$	$V_{liq} = \frac{M_{sol}}{s \times G_{sup}} \times 100$	$V_w = V_{liq} \times G_{sup} \times \left(\frac{100 - s}{100}\right)$	$V_{sol} = V_{liq} - V_w$
1.21	40	3.575	7.4	5.0	2.0

	1		2	3	4	5	6	
Materials	Content (kg/m^3)		Volume (litre/m^3)	Dosage SSD (kg/m^3)	Water correction (litre/m^3)	Composition (m3) 1 m^3	0.00165	m^3
w/b ratio	0.3							
water	165.00		165.00	165.00		198.0	0.3267	litre
cement	550	275	87.00	275.00		275.0	0.4538	kg
ultra fine fly ash		275	126.00	275.00		275.0	0.4538	kg
-								
Coarse Agregate	1,000.00		357.00	1000.00	24.00	976.0	1.6105	kg
Fine aggregate			226.00	598.90	14.00	585.0	0.9653	kg
						1,561.0	**2.5758**	
Air	1.20%		12.00	0.00				
Superplasticizer	0.65%			4.00	-5.00	7.4	0.0122	litre
Total			749.00	2,318.00	33.00			

Appendix C.2: Mix proportions of high volume raw fly ash mortar

MIX DESIGN SHEET: High volume raw fly ash mortar

Comp. Strength : 80 MPa

Table A	Spec. Gravity	%
Cement	3.15	50.00%
raw fly ash	2.01	50.00%

Aggregate	G_{SSD}	% W_{abs}	W_{tot}	W_h
Coarse	2.80	2.4	0	-2.4
Fine	2.65	3.9	1.5	-2.4

$W_h = w_{tot} - w_{abs}$ $M = M_{SSD} \times (1 + w_h)$

Superplasticizer

G_{sup}	Solid dosage s (%)	$M_{sol} = C \times \frac{d}{100}$	$V_{liq} = \frac{M_{sol}}{s \times G_{sup}} \times 100$	$V_w = V_{liq} \times G_{sup} \times \left(\frac{100 - s}{100}\right)$	$V_{sol} = V_{liq} - V_w$
1.21	40	7.04	14.5	11.0	4.0

	1		2	3	4	5	6	
Materials	Content (kg/m^3)		Volume (litre/m^3)	Dosage SSD (kg/m^3)	Water correction (litre/m^3)	Composition (m3) 1 m^3	0.00165	m^3
w/b ratio	0.3							
water	165.00		165.00	165.00		192.0	0.3168	litre
cement	550	275	87.00	275.00		275.0	0.4538	kg
raw fly ash		275	137.00	275.00		275.0	0.4538	kg
-								
Coarse Agregate	1,000.00		357.00	1000.00	24.00	976.0	1.6105	kg
Fine aggregate			214.00	567.10	14.00	553.0	0.9125	kg
						1,529.0	**2.5230**	
Air	1.20%		12.00	0.00				
Superplasticizer	1.28%			7.00	-11.00	14.5	0.0239	litre
Total			762.00	2,289.00	27.00			

Appendix C.3: Mix proportions of high strength OPC mortar

MIX DESIGN SHEET: High strength OPC mortar

Comp. Strength : 80 MPa

Table A	Spec. Gravity	%
Cement	3.15	100.00%
fly ash	2.01	0.00%

Aggregate	G_{SSD}	% W_{abs}	% W_{tot}	% W_h
Coarse	2.80	2.4	0	-2.4
Fine	2.65	3.9	1.5	-2.4

$W_h = w_{tot} - w_{abs}$

$M = M_{SSD} \times (1 + w_h)$

Superplasticizer

G_{sup}	Solid dosage s (%)	$M_{sol} = C \times \frac{d}{100}$	$V_{liq} = \frac{M_{sol}}{s \times G_{sup}} \times 100$	$V_w = V_{liq} \times G_{sup} \times \left(\frac{100 - s}{100}\right)$	$V_{sol} = V_{liq} - V_w$
1.21	40	9.24	19.1	14.0	5.0

	1		2	3	4	5	6	
Materials	Content (kg/m^3)		Volume ($litre/m^3$)	Dosage SSD (kg/m^3)	Water correction ($litre/m^3$)	Composition (m3) 1 m^3	0.00165	m^3
w/b ratio	0.3							
water	165.00		165.00	165.00		192.0	0.3168	litre
cement	550	550	175.00	550.00		550.0	0.9076	kg
fly ash		0	0.00	0.00		-	-	kg
-								
Coarse Agregate	1,000.00		357.00	1000.00	24.00	976.0	1.6105	kg
Fine aggregate			260.00	689.00	17.00	672.0	1.1089	kg
						1,648.0	**2.7194**	
Air	1.20%		12.00	0.00				
Superplasticizer	1.68%			9.00	-14.00	19.1	0.0315	litre
Total			714.00	2,413.00	27.00			

Appendix D.1: Mix design of high volume ultra fine fly ash concrete use basalt fibre (Mix proportion No 1)

MIX DESIGN SHEET: high volume ultra fine fly ash use basalt fibre

Comp. Strength : 80 MPa

Table A	Spec. Gravity	%
Cement	**3.15**	**50.00%**
fly ash	**2.18**	**50.00%**
Ultra fine		**0.00%**

Mortar test

Aggregate	G_{SSD}	W_{abs} (%)	W_{tot} (%)	W_h (%)
Coarse	**2.89**	**0.8**	**0.2**	-0.6
Fine	**2.60**	**1.4**	**0.8**	-0.6

$W_h = w_{tot} - w_{abs}$ $M = M_{SSD} \times (1 + w_h)$

Superplasticizer

G_{sup}	Solid dosage s (%)	$M_{sol} = C \times \frac{d}{100}$	$V_{liq} = \frac{M_{sol}}{s \times G_{sup}} \times 100$	$V_w = V_{liq} \times G_{sup} \times \left(\frac{100 - s}{100}\right)$	$V_{sol} = V_{liq} - V_w$
1.21	**40**	3.375	7	5.0	2.0

	1		2	3	4	5	6	
Materials	Content (kg/m^3)		Volume ($litre/m^3$)	Dosage SSD (kg/m^3)	Water correction ($litre/m^3$)	Composition (m3) 1 m^3	**0.08500**	m^3
w/b ratio	0.3							
water	135.00		135.00	135.00		141.0	11.9850	litre
cement	450	225	71.00	225.00		225.0	19.1250	kg
fly ash		225	103.00	225.00		225.0	19.1250	kg
Ultra fine								
Coarse Agregate	1,000.00		346.00	1000.00	6.00	994.0	84.4900	kg
Fine aggregate			313.00	813.80	5.00	809.0	68.7650	kg
Air	1.20%		12.00	0.00				
Superplasticizer	**0.75%**			3.00	-5.00	7.0	0.5950	litre
Basalt fibre	**1.00%**		10.00	26.70		26.7	2.1867	kg
Total			679.00	2,428.50	6.00			

Appendix D.2. Mix design of high volume ultra fine fly ash concrete without basalt fibre (Mix proportion No 2)

MIX DESIGN SHEET: high volume ultra fine fly ash without basalt fibre

Comp. Strength : 80 MPa

Table A	Spec. Gravity	%
Cement	**3.15**	**50.00%**
ultra fine fly ash	**2.18**	**50.00%**
		0.00%

Mortar test

Aggregate	G_{SSD}	W_{abs} (%)	W_{tot} (%)	W_h (%)
Coarse	**2.89**	**0.8**	**0.2**	-0.6
Fine	**2.60**	**1.4**	**0.8**	-0.6

$W_h = w_{tot} - w_{abs}$ $M = M_{SSD} \times (1 + w_h)$

Superplasticizer

G_{sup}	Solid dosage s (%)	$M_{sol} = C \times \frac{d}{100}$	$V_{liq} = \frac{M_{sol}}{s \times G_{sup}} \times 100$	$V_w = V_{liq} \times G_{sup} \times \left(\frac{100 - s}{100}\right)$	$V_{sol} = V_{liq} - V_w$
1.21	**40**	3.375	7	5.0	2.0

	1		2	3	4	5	6	
Materials	Content (kg/m^3)		Volume ($litre/m^3$)	Dosage SSD (kg/m^3)	Water correction ($litre/m^3$)	Composition (m3) 1 m^3	**0.085**	m^3
w/b ratio	0.3							
water	135.00		135.00	135.00		141.0	11.9850	litre
cement	450	225	71.00	225.00		225.0	19.1250	kg
ultra fine fly ash		225	103.00	225.00		225.0	19.1250	kg
Ultra fine								
Coarse Agregate	1,000.00		346.00	1000.00	6.00	994.0	84.4900	kg
Fine aggregate			323.00	839.80	5.00	835.0	70.9750	kg
Air	1.20%		12.00	0.00				
Superplasticizer	**0.75%**			3.00	-5.00	7.0	0.5950	litre
Basalt fibre	**1.00%**					-	-	kg
Total			669.00	2,427.80	6.00			

Appendix D.3. Mix design of high volume raw fly ash concrete use basalt fibre (Mix proportion No 3)

MIX DESIGN SHEET: high volume raw fly ash use basalt fibre

Comp. Strength : 80 MPa

Table A	Spec. Gravity	%
Cement	**3.15**	**50.00%**
raw fly ash	**2.01**	**50.00%**
		0.00%

Aggregate	G_{SSD}	% W_{abs}	% W_{tot}	% W_h
Coarse	**2.89**	**0.8**	**0.2**	-0.6
Fine	**2.60**	**1.4**	**0.8**	-0.6

$W_h = w_{tot} - w_{abs}$ $M = M_{SSD} \times (1 + w_h)$

Superplasticizer

G_{sup}	Solid dosage s (%)	$M_{sol} = C \times \frac{d}{100}$		$V_{liq} = \frac{M_{sol}}{s \times G_{sup}} \times 100$	$V_w = V_{liq} \times G_{sup} \times \left(\frac{100 - s}{100}\right)$		$V_{sol} = V_{liq} - V_w$
1.21	**40**	4.95		10.2	7.0		3.0

	1		2	3	4	5	6	
Materials	Content (kg/m^3)		Volume ($litre/m^3$)	Dosage SSD (kg/m^3)	Water correction ($litre/m^3$)	Composition (m3) 1 m^3	**0.085**	m^3
w/b ratio	0.3							
water	135.00		135.00	135.00		139.0	11.3838	litre
cement	450	225	71.00	225.00		225.0	18.4270	kg
raw fly ash		225	112.00	225.00		225.0	0.3713	kg
-								
Coarse Agregate	1,000.00		346.00	1000.00	6.00	994.0	81.4064	kg
Fine aggregate			304.00	790.40	5.00	785.0	64.2898	kg
Air	1.20%		12.00	0.00				
Superplasticizer	**1.10%**			5.00	-7.00	10.2	0.8354	litre
Basalt fibre	**1.00%**		10.00	26.70		26.7	2.1867	
Total			689.00	2,407.10	4.00			

Appendix D.4. Mix design of high volume raw fly ash concrete without basalt fibre (Mix proportion No 4)

MIX DESIGN SHEET: high volume raw fly ash without basalt fibre

Comp. Strength : 80 MPa

Table A	Spec. Gravity	%
Cement	**3.15**	**50.00%**
raw fly ash	**2.01**	**50.00%**
		0.00%

Aggregate	G_{SSD}	% W_{abs}	% W_{tot}	% W_h
Coarse	**2.89**	**0.8**	**0.2**	-0.6
Fine	**2.60**	**1.4**	**0.8**	-0.6

$W_h = w_{tot} - w_{abs}$ $M = M_{SSD} \times (1 + w_h)$

Superplasticizer

G_{sup}	Solid dosage s (%)	$M_{sol} = C \times \frac{d}{100}$		$V_{liq} = \frac{M_{sol}}{s \times G_{sup}} \times 100$	$V_w = V_{liq} \times G_{sup} \times \left(\frac{100 - s}{100}\right)$		$V_{sol} = V_{liq} - V_w$
1.21	**40**	4.95		10.2	7.0		3.0

	1		2	3	4	5	6	
Materials	Content (kg/m^3)		Volume ($litre/m^3$)	Dosage SSD (kg/m^3)	Water correction ($litre/m^3$)	Composition (m3) 1 m^3	**0.00165**	m^3
w/b ratio	0.3							
water	135.00		135.00	135.00		139.0	11.3838	litre
cement	450	225	71.00	225.00		225.0	18.4270	kg
raw fly ash		225	112.00	225.00		225.0	0.3713	kg
-						**4.01**		
Coarse Agregate	1,000.00		346.00	1000.00	6.00	994.0	81.4064	kg
Fine aggregate			314.00	816.40	5.00	811.0	66.4191	kg
						1,805.0	**147.826**	
Air	1.20%		12.00	0.00				
Superplasticizer	**1.10%**			5.00	-7.00	10.2	0.8354	litre
Basalt fibre	**0.00%**		0.00	0.00		-	-	
Total			679.00	2,406.40	4.00			

Appendix D.5. Mix design of high strength OPC concrete without basalt fibre (Mix proportion No 5)

MIX DESIGN SHEET: OPC concrete

Comp. Strength : 80 MPa

Table A	Spec. Gravity	%
Cement	**3.15**	**100.00%**
fly ash	**2.01**	**0.00%**
		0.00%

Aggregate	G_{SSD}	% W_{abs}	% W_{tot}	% W_h
Coarse	**2.89**	**0.8**	**0.2**	-0.6
Fine	**2.60**	**1.4**	**0.8**	-0.6

$W_h = w_{tot} - w_{abs}$ $M = M_{SSD} \times (1 + w_h)$

Superplasticizer

G_{sup}	Solid dosage s (%)	$M_{sol} = C \times \frac{d}{100}$		$V_{liq} = \frac{M_{sol}}{s \times G_{sup}} \times 100$	$V_w = V_{liq} \times G_{sup} \times \left(\frac{100 - s}{100}\right)$		$V_{sol} = V_{liq} - V_w$
1.21	**40**	6.75		13.9	10.0		4.0

	1		2	3	4	5	6	
Materials	Content (kg/m^3)		Volume ($litre/m^3$)	Dosage SSD (kg/m^3)	Water correction ($litre/m^3$)	Composition (m3) 1 m^3	**0.00165**	m^3
w/b ratio	0.3							
water	135.00		135.00	135.00		136.0	11.1381	litre
cement	450	450	143.00	450.00		450.0	36.8540	kg
fly ash		0	0.00	0.00		-	-	kg
-								
Coarse Agregate	1,000.00		346.00	1000.00	6.00	994.0	81.4064	kg
Fine aggregate			343.00	891.80	5.00	887.0	72.6433	kg
Air	1.20%		12.00	0.00				
Superplasticizer	**1.50%**			7.00	-10.00	13.9	1.1384	litre
Basalt fibre	**1.00%**		10.00	26.70		26.7	2.1867	
Total			650.00	2,510.50	1.00			

Appendix D.6. Mix design of high strength OPC concrete use basalt fibre (Mix proportion No 6)

MIX DESIGN SHEET: OPC concrete use basalt fibre

Comp. Strength : 80 MPa

Table A	Spec. Gravity	%
Cement	**3.15**	**100.00%**
fly ash	**2.01**	**0.00%**
		0.00%

Aggregate	G_{SSD}	% W_{abs}	% W_{tot}	% W_h
Coarse	**2.89**	**0.8**	**0.2**	-0.6
Fine	**2.60**	**1.4**	**0.8**	-0.6

$W_h = w_{tot} - w_{abs}$ $M = M_{SSD} \times (1 + w_h)$

Superplasticizer

G_{sup}	Solid dosage s (%)	$M_{sol} = C \times \frac{d}{100}$		$V_{liq} = \frac{M_{sol}}{s \times G_{sup}} \times 100$	$V_w = V_{liq} \times G_{sup} \times \left(\frac{100 - s}{100}\right)$		$V_{sol} = V_{liq} - V_w$
1.21	**40**	6.75		13.9	10.0		4.0

	1		2	3	4	5	6	
Materials	Content (kg/m^3)		Volume ($litre/m^3$)	Dosage SSD (kg/m^3)	Water correction ($litre/m^3$)	Composition (m3) 1 m^3	**0.081898**	m^3
w/b ratio	0.3							
water	135.00		135.00	135.00		137.0	11.2200	litre
cement	450	450	143.00	450.00		450.0	36.8540	kg
fly ash		0	0.00	0.00		-	-	kg
-						**4.24**		
Coarse Agregate	1,000.00		346.00	1000.00	6.00	994.0	81.4064	kg
Fine aggregate			353.00	917.80	6.00	912.0	74.6908	kg
						1,906.0	**156.10**	
Air	1.20%		12.00	0.00				
Superplasticizer	**1.50%**			7.00	-10.00	13.9	1.1384	litre
Total			640.00	2,509.80	2.00			

Appendix D.7. Mix design of high strength OPC concrete use steel fibre (Mix proportion No 7)

MIX DESIGN SHEET: OPC concrete use steel fibre

Comp. Strength : 80 MPa

Table A	Spec. Gravity	%
Cement	**3.15**	**100.00%**
fly ash	**2.01**	**0.00%**
		0.00%

Aggregate	G_{SSD}	% W_{abs}	% W_{tot}	% W_h
Coarse	**2.89**	**0.8**	**0.2**	-0.6
Fine	**2.60**	**1.4**	**0.8**	-0.6

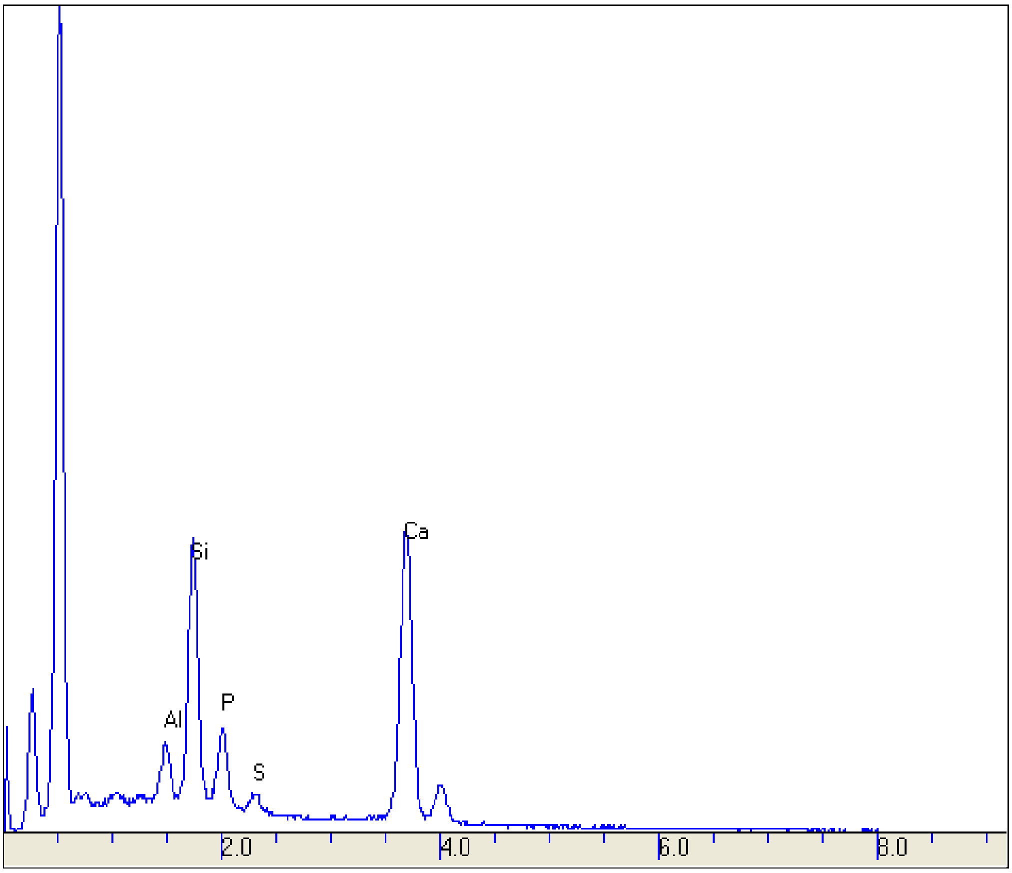
$W_h = w_{tot} - w_{abs}$ $M = M_{SSD} \times (1 + w_h)$

Superplasticizer

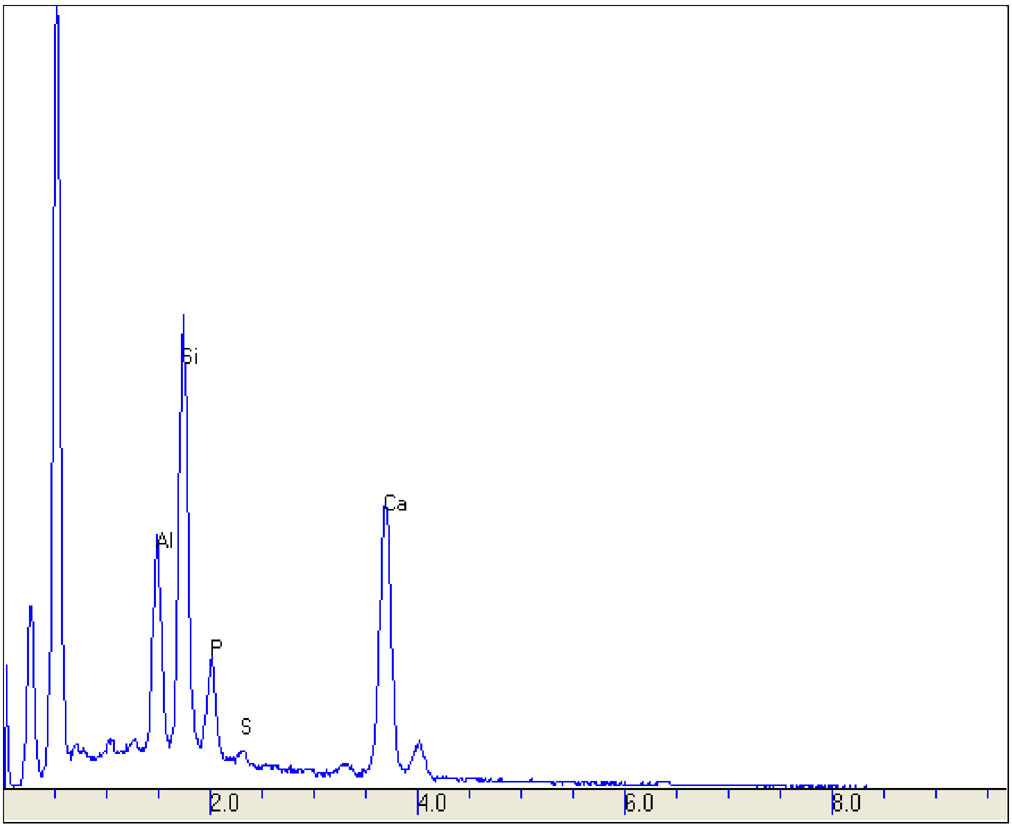
G_{sup}	Solid dosage s (%)	$M_{sol} = C \times \frac{d}{100}$		$V_{liq} = \frac{M_{sol}}{s \times G_{sup}} \times 100$	$V_w = V_{liq} \times G_{sup} \times \left(\frac{100 - s}{100}\right)$		$V_{sol} = V_{liq} - V_w$
1.21	**40**	6.75		13.9	10.0		4.0

	1		2	3	4	5	6	
Materials	Content (kg/m^3)		Volume (litre/m^3)	Dosage SSD (kg/m^3)	Water correction (litre/m^3)	Composition (m3) 1 m^3	**0.081898**	m^3
w/b ratio	0.3							
water	135.00		135.00	135.00		136.0	11.1381	litre
cement	450	450	143.00	450.00		450.0	36.8540	kg
fly ash		0	0.00	0.00		-	-	kg
-								
Coarse Agregate	1,000.00		346.00	1000.00	6.00	994.0	81.4064	kg
Fine aggregate			343.50	893.10	5.00	888.0	72.7252	kg
Air	1.20%		12.00	0.00				
Superplasticizer	**1.50%**			7.00	-10.00	13.9	1.1384	litre
Steel fibre	**1.00%**		10.00	75.00		75.0	6.1423	
Total			650.00	2,560.10	1.00			

Appendix E.1: EDAX analysis for High volume ultra fine fly ash with saturated lime water binder



Appendix E.2: EDAX analysis for High volume raw fly ash binder



Appendix E.3: EDAX analysis for OPC binder